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MATERIAL REQUIREMENTS PLANNING IN AIR FORCE DEPOT-LEVEL MAINTENANCE

THESIS

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Acknowledgments

It has often been said that behind every successful man is a great woman. I'm blessed to have four. To my wife and best friend Kathy and my daughters Megan, Kelsey, and Amanda, I am deeply indebted for their patience through this long and painful endeavor. I only hope that I can repay them some day for their support.

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I leave with a pearl of wisdom from T. S. Eliot to those that follow:

> Where is the life we have lost in living?
>
> Where is the wisdom we have lost in knowledge?
>
> Where is the knowledge we have lost in information?

Kevin J. Gaudette

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Abstract

The Department of Defense has historically relied on Wilson's Economic Order Quantity (EOQ) model for consumable item management at all levels. With inventory practices under intense Congressional scrutiny over the past decade, the Air Force Materiel Command has searched for alternative systems to better manage its consumable inventory. Material Requirements Planning (MRP) is one such system, as is the MRP-based Repairability Forecast Model (RFM) developed by CACI. This thesis examines the wisdom of applying MRP logic in a remanufacturing environment. MRP has had some degree of success in environments where requirements are relatively certain and demand and lead time variability are not excessive. A remanufacturing operation, in contrast, is typified by a great deal of variability and uncertainty due to the very nature of repair.

The experimental methodology involved the development of computer simulation models of EOQ and MRP systems. Demand uncertainty, demand variability, and lead time variability were then varied at three levels each to develop a full factorial experimental design. The results were used to test EOQ and MRP using two different performance measures: average number of awaiting parts (AWP) days per repair and total annual inventory cost.

The results lend support for the use of MRP in a remanufacturing environment. The number of AWP days was significantly reduced from that of the EOQ system, albeit at an increased inventory cost. When the two measures are combined, however, MRP appears to outperform EOQ in aggregate

MATERIAL REQUIREMENTS PLANNING

IN AIR FORCE DEPOT-LEVEL MAINTENANCE

I. Background and Problem Presentation

Introduction

The effect of irregular, or "lumpy," demand on stock levels has historically been a pervasive problem throughout the defense community. In the case of consumable items, the problem is exacerbated by the use of Wilson's Economic Order Quantity (EOQ) model, which does not always perform well in highly variable environments. The EOQ model is built upon many assumptions, some of which are invalid in practice. Yet minor violations of these assumptions do not significantly affect the minimization of total cost, due to the robustness of the model. However, as the violations worsen in magnitude, the effects on stock availability, and therefore readiness, can be substantial. This study looks at Material Requirements Planning (MRP) as an alternative to the EOQ model for ordering of consumable items at Air Force depots.

The Air Logistics Center (ALC) Environment

The Air Force currently performs the majority of weapon system maintenance at two levels, hence the term "two-level maintenance." The lower of the two levels is the Air Force base, where maintenance technicians repair a percentage of reparable parts on site. The upper level is the Air Logistics Center (ALC), or "depot," where more complex repairs are accomplished. When a reparable part malfunctions at a base, it is either repaired locally or it is sent to the depot for repair. In the latter case, a serviceable part is sent to the base immediately if available, to either replenish stock or repair the "end-item." The defective part, upon arrival at the

depot, enters a pool of items waiting to be repaired and returned into serviceable stock. This process is illustrated in Figure 1 below.

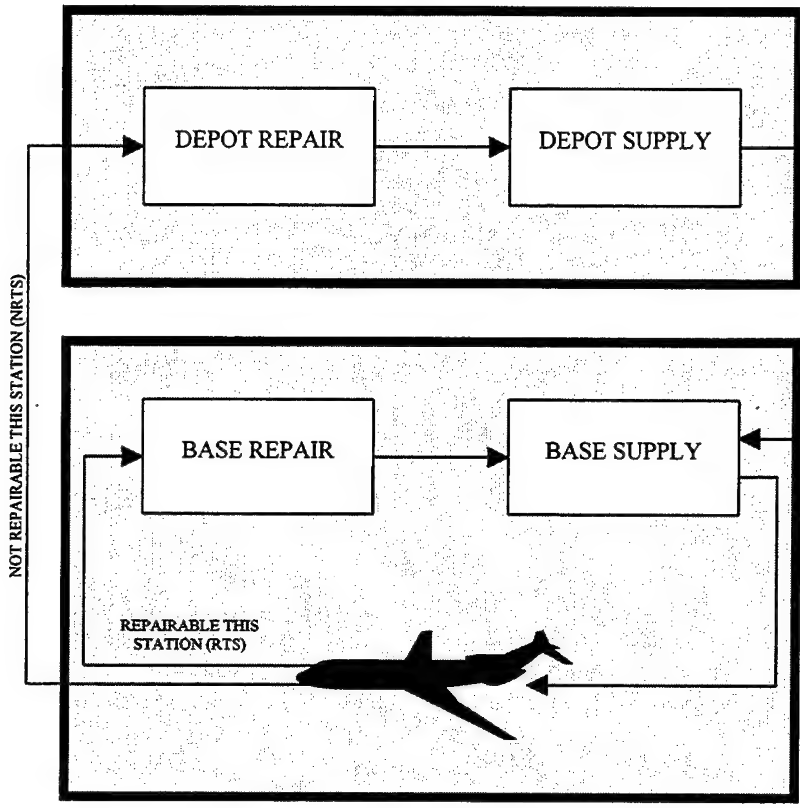


Figure 1: Air Force Two-Level Maintenance

From an inventory perspective, depots need consumable parts to accomplish repairs in response to base demands. Under current DoD policy, the Defense Logistics Agency (DLA) is charged with supplying the majority of these consumable spare parts (Hanks, 1990: 1-1). Considering the entire inventory hierarchy, reparable failures at the base level drive depot repairs. The level of repair activity at the depot then creates a demand for consumable parts, which is used to place replenishment orders to DLA. Demands from all Air Force depots, as well as those from the other services and individual bases, are then aggregated at DLA and become DLA's total

demand. At each level, variations of Wilson's EOQ formula are used to compute order quantities. The inventory process is shown graphically in Figure 2.

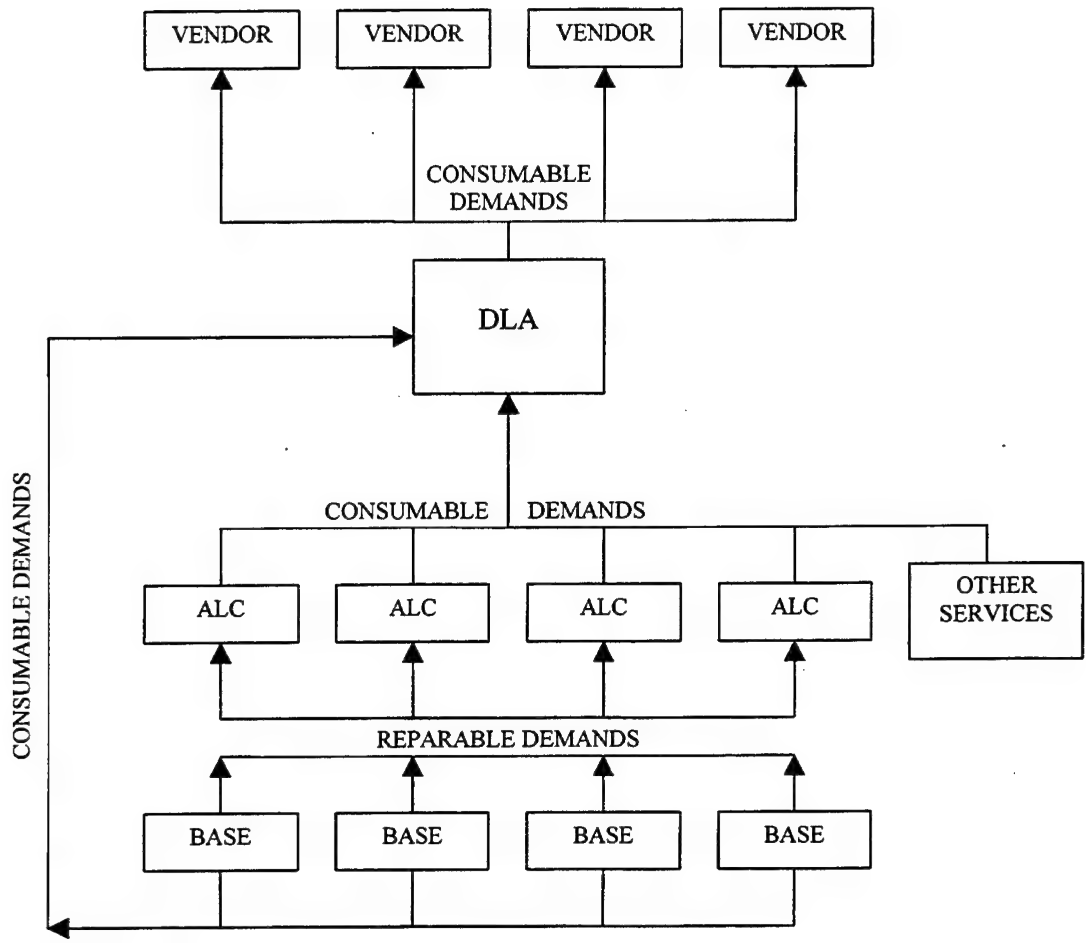


Figure 2: Flow of Demand for Consumable Parts

Agile Logistics: A Changing Environment

With the advent of the Air Force "Agile Logistics" program (formerly "Lean Logistics"), increased emphasis has been placed on the efficiency of depot repairs. Perhaps the largest paradigm shift is that of On-Condition Maintenance (OCM), which is replacing batch processing. Traditionally, depots would batch repairs into groups and perform complete overhauls. Although

batch processing caused demand patterns to be irregular in many cases, the complete overhaul philosophy meant that consumable item requirements could be forecasted relatively easily.

OCM, in contrast, emphasizes replacing or repairing only those parts that have caused a malfunction. This change in philosophy brings with it a whole host of problems, not the least of which is its impact on demand patterns. Under the OCM concept, not only is the quantity of each item subject to variability, but the items required are variable as well. For example, in an overhaul repair 2 units of part A may be required, 65 of part B, and 10 of part C. If the same end-item is inducted as an OCM repair, parts A and C may not be repaired or replaced at all, and only 12 of part B may be required. This exacerbates the variability problem in an already highly variable environment. In addition to the shift to OCM, budget constraints have reduced spare stock levels to the point where demand variability has become even more critical. As a result, there is a need for an accompanying paradigm shift in the area of inventory management in order for Agile Logistics to be successful.

The transfer of consumable item management to DLA has added to the challenges posed by the evolution to Agile Logistics. With inventory control taken out of ALC hands, material-ordering policies will become a critical element in their success. The Oklahoma City Air Logistics Center (OC-ALC) is one such depot, managing a wide range of defense systems. Its Propulsion Directorate (LP) manages a number of aircraft engines, which play a critical role in aircraft availability throughout the Air Force. Like most depot directorates, LP relies on DLA for most of their consumable parts. Facing a growing list of production "pacing items," or parts that hold up production if not available, LP has searched for alternative ways of managing its material requirements.

Based in part on the findings of a study of its backorders by Dynamics Research Corporation, the LP Directorate contracted with CACI to implement its Repairability Forecast Model (RFM) at the center. The model, originally developed under contract with the San

Antonio Air Logistics Center (SA-ALC), follows the logic of a traditional Material Requirements Planning (MRP) system, drawing data from legacy systems to build inventory reports for management use (Draper, 1997: 2). In particular, RFM uses data from the bill of materials; production schedules; and inventory, contracting, and finance databases to determine material requirements to meet projected production. Unlike most MRP systems, however, RFM does not have the capability to actually place necessary orders. Depot production and supply personnel, therefore, must use the reports generated by RFM to determine requirements and place orders where necessary. At the theoretical level, RFM is designed to use existing databases to generate supportability assessments, which allow ALC personnel to solve material shortages before they hold up production.

Problem Statement

The overarching problem is the readiness of Air Force weapon systems, which is indirectly tied to parts availability. Lack of engine parts at OC-ALC, for example, leads to a greater quantity of engines awaiting repair. This, in turn, leads to a smaller number of serviceable spare engines, which affects aircraft availability. The problem addressed by the LP Directorate was the selection of an inventory management system to more effectively support the determination of material requirements for production. Following the lead of the San Antonio Air Logistics Center (SA-ALC), OC-ALC/LP decided to install RFM at its facility.

Computer systems can be costly, however, in terms of both capital investment and life cycle maintenance. As such, a great deal of care must be taken in selecting a system that will perform as intended. To date, no analysis has been performed to test the anticipated effectiveness of MRP logic in a depot engine repair shop. It is this gap that the present study attempts to fill. The research problem addressed in this study, then, is that of the appropriateness of the use of MRP in managing inventory requirements for depot repair in general, and specifically in an OCM production environment.

Research Objectives

The primary objectives of this research are to test MRP logic in an Air Logistics Center environment and to compare its performance with that of the EOQ model. The secondary objective is to determine if RFM is an appropriate system, based on the system's characteristics and the results of the research. First, a review of EOQ and MRP systems is necessary to provide insight into the theory and methodology that form the basis for the models. Second, the models must be analyzed from the perspective of existing research in the field of inventory management. Finally, simulation modeling is used to test the performance of MRP, the results of which can be compared with the performance of the EOQ to predict the magnitude of any expected benefits. In essence, the primary objectives aim to determine whether or not MRP is the correct tool for the job. By inference, then, RFM can be assumed to provide similar performance due to its reliance on MRP logic.

In addition to the primary objectives stated above, assuming the benefits of RFM are found to be realizable, procedural guidance is needed for the successful use of the system. Even if the expected benefits are found to be realistic in theory, successful use of the system will depend almost solely on management emphasis, training, and carefully developed procedures.

Research Questions

To achieve the research objectives, specific research questions must be addressed. These are listed below chronologically, in terms of the order of research conducted.

1. Does the EOQ model adequately meet the needs of the Air Logistics Centers in ensuring consumable parts availability?
2. Would the use of Material Requirements Planning improve inventory availability?
3. Can RFM be assumed to perform at the same level as MRP, given their similarities and differences?

4. What procedural measures are necessary to ensure RFM's success?

Hypothesis

The tests of the hypothesis will be based both on the literature review of existing research and on the results of a simulation experiment. A great deal of research has been conducted in recent years in the area of inventory management and, in particular, MRP systems. This research has isolated many of the specific advantages and disadvantages of such systems, and will be used to help answer the research questions above. The results of a simulation model will then be used to specifically answer question 2. The hypothesis is given below.

Null Hypothesis: The use of MRP is inappropriate given the characteristics of production and inventory at the OC-ALC LP Directorate.

Alternative Hypothesis: The use of MRP is appropriate given the characteristics of production and inventory at the OC-ALC LP Directorate, and it can be expected to outperform traditional EOQ models in terms of applicable performance measures.

Methodology Overview

The primary tool used in this research is simulation modeling. Due to the nature and complexity of the problem, simulation has been determined to be superior to other tools. Simulation modeling is a flexible, low cost, and easily controllable means of studying systems under varying conditions, and as such it provides an excellent tool to estimate system behavior. It also allows a large number of "what ifs" to be asked by the researcher quickly and with low risk (Law and Kelton, 1991: 115).

A comparison of the EOQ and MRP models will be conducted using the results of the model simulation. Results will be analyzed using traditional statistical techniques to determine if any differences are statistically significant. In addition, the simulation factors will be

systematically modified to analyze the effects of different environments on system performance. A detailed description of the methodology is provided in Chapter III.

Scope

The problem of analyzing the performance of inventory systems in an environment such as a military depot is extremely complex. The sheer number of items stocked, as well as the complexity of the repair process, make it difficult to conduct a broad study. As such, the scope of this research has been reduced for feasibility reasons. The first constraint imposed in this study is the use of data from a single engine component. The component under analysis was selected to represent the full range of parts problems experienced by an engine repair depot. This simplifies the simulation problem considerably, while maintaining most of the generalizability of results to other components and engine types. Simply stated, if MRP outperforms EOQ for the worst-case components, it can be assumed to outperform EOQ for others as well, albeit by different magnitudes.

The simulation study was also limited to consumable items. Although RFM can, and probably will, be used to assess both consumables and reparables, the former are generally found at lower levels of indenture, and as such experience a greater degree of "system nervousness" (Tersine, 1994: 360). This is due to the magnification of variability with each subsequent level of indenture. Again, if MRP outperforms EOQ in the worst case, it can be assumed to do the same for higher levels of indenture.

Finally, a sample of the population data was used for model formulation. Although some degree of accuracy is forfeited by using only a fraction of the total population of items, the time saved allows for a more intensive analysis. This includes a greater range of factors, as well as a stratification of factors to determine their impact on system performance.

Assumptions

A number of assumptions are inherent to a study of this nature. The first, and most basic, is the assumption that the sample data selected are representative of the population of all consumable items for the selected components. These data are also assumed to be representative of expected future data, since if demand or repair data changes in nature, the results of this study may become invalid.

Obviously, the inherent assumptions of the two models being compared must also hold in this study. The EOQ model, as previously mentioned, is laden with many such assumptions. In developing the model, these same assumptions will necessarily remain intact. The MRP model makes its own set of assumptions, and the same logic therefore applies.

Finally, production capability is assumed to be equal to demand in all shops within the LP Directorate. Although technically not the case, it is nevertheless necessary to make this assumption in order to limit analysis to inventory management alone. In this way, a degree of experimental control is established. In short, this study is not concerned with production bottlenecks, unless they have been caused by material shortages. A more detailed look at the simulation model assumptions is provided in Chapter III.

Limitations

Although this study will attempt to answer the research question specific to the use of RFM, the simulation model will use traditional MRP theory as its basis. The results must therefore be viewed with some caution, since RFM is not specifically the system under study. Insofar as RFM is found to adhere to MRP theory, however, the results of the simulation can be applied to RFM as well. Any significant differences between RFM and MRP with regard to their methodology, scope, and objectives will be addressed as procedural guidance in Chapter V.

Management Implications

As the Air Force Materiel Command (AFMC) considers including RFM in its "standard suite" of computer systems for the Air Logistics Centers, the results of this research can be invaluable. Instituting a computer system without properly testing its logic is ill advised, as is instituting a system without carefully considering the associated procedural, training, and management issues. This study will not only test the *appropriateness of using* MRP in a depot environment, but will also recommend its *appropriate use*.

Organization of Research

Chapter I has introduced the background of the problem being studied at the OC-ALC, and has attempted to put it into the context of the greater body of inventory management theory. It has further introduced the research objectives and questions that drove the study, and has provided an overview of the methodology, scope, and assumptions used. Finally, the limitations and management implications have been discussed in an attempt to tie the results to real-world application.

In Chapter II, an exhaustive review of applicable research is presented in the area of inventory management. The classic EOQ and MRP models are described and analyzed, with strengths and weaknesses identified from the literature. Studies dealing specifically with defense systems are also reviewed to further clarify the extent of the problems.

Chapter III lays the foundation of the simulation experiment and its methodology. A detailed description of the simulation models and experimental design is presented, as well as a description of the data collection methods employed. Finally, the plan for analyzing the data and formulating the results is presented.

Chapter IV presents the data output from the simulation experiment, the statistical analysis of the data, and the results of the experiment.

In Chapter V, overall conclusions are drawn from the results. Results are examined, and suggestions for implementation and procedural guidance are offered. Areas for potential future research are also offered.

II. Literature Review

Introduction

Since the focus of this study is a comparison between existing Air Logistics Center consumable inventory management (EOQ) and an MRP system in the same environment, it is first necessary to understand the theory behind each. Following each of the general theoretical explanations is a discussion of each system in light of existing research, to include how each performs under a wide range of environmental factors. In addition to the EOQ and MRP models, an understanding of several alternative inventory models is necessary, since much of the existing research regarding EOQ and MRP encompasses these models as well. With the theoretical foundation laid, a discussion of the appropriateness of the MRP model in Air Force depot maintenance environments is possible. Finally, the RFM system is described and contrasted with traditional MRP systems. This discussion includes the historical need for its development, its similarities and differences to the classic MRP model, and the appropriateness of its use given the characteristics of military depot engine repair.

Inventory Management Overview

Many techniques have been developed over the years to manage inventory requirements. Although management techniques vary significantly in their theoretical foundations, they all have a common goal: efficient management of inventory. Inventory can be categorized into different classes, each serving a specific purpose. These classes, although transparent in physical terms, are important in terms of understanding the composition of the overall stock level. A brief explanation of the most common classifications follows, in order to build a framework for subsequent discussions of specific techniques.

The first and usually largest classification is working inventory. Working inventory is acquired in anticipation of future requirements, and is generally necessary to minimize inventory-related costs. In the classic economic order quantity (EOQ) model, for example, lot sizes are selected to minimize the sum of holding and ordering costs. These lot sizes may then be adjusted upward to qualify for quantity discounts or lower transportation rates (Tersine, 1994: 7-8). Working inventory levels are calculated using any number of techniques, but they generally use a discrete estimate of future demand. Since it is unlikely that demand and lead times will be exactly as planned, other classifications of inventory are used to account for the probable variations.

Safety, or "buffer," inventory is used to protect against stockouts during a replenishment cycle (Tersine, 1994: 206). Without adequate safety stock, any increase in demand while waiting for a replenishment will result in such a stockout. Safety stock adds to the overall holding cost, however, which provides incentive to minimize it within service level constraints. These constraints are calculated using stockout costs, and so safety levels must be chosen carefully to minimize the *sum* of stockout and holding costs. Stockout costs come in two varieties, depending on the organization and product. The first is the backorder cost, which implies that the customer will wait for the item while it is ordered. Backorder costs can be due to expediting costs, handling costs, and higher transportation rates (Tersine, 1994: 207). The other variety of stockout cost is lost sales, which can include both direct loss of profit and some level of customer dissatisfaction (Tersine, 1994: 208). In the military, sales are not lost since it is its own supplier. Mission degradation, however, can be viewed as its military equivalent.

A third classification of inventory is anticipation inventory. Like working inventory, anticipation inventory is acquired in advance of requirements. The difference is that the latter is generally associated with an anticipated spike in demand (Tersine, 1994: 8). In retail sales, for example, seasonal fluctuations in demand for certain clothing items can be dealt with using a

level of anticipation inventory. Wherever working inventory is calculated using projected demands, working and anticipation inventories can effectively be combined.

Pipeline inventory is inventory that is either in transportation or production channels. The former, usually external to the organization, is stock that is in transit either into or out of the organization. The latter is internal, and is generally referred to as "work-in-process," or "WIP" (Tersine, 1994: 8). Although seemingly negligible, pipeline stock can be significant in systems that involve long production and transportation processes.

The final inventory classification of interest is decoupling inventory. This type can be described as "lubrication...that protects [the system] against excessive friction" (Tersine, 1994: 8). In essence, decoupling stock is held at each activity or stage in a process to allow for a continuous flow despite the inherent lack of synchronization experienced in most systems. For example, the variability in production times for a certain work station may result in occasional idle time at the next work station. The latter may elect to maintain a level of decoupling inventory to enable it to continue production until the former "catches up."

With the different classifications of inventory explained and understood, it is now possible to discuss different inventory theories and the methods they employ to balance costs and service levels. Economic Order Quantity (EOQ) theory is a popular simplistic approach that attempts to balance ordering and holding costs, thereby minimizing the total cost (Tersine, 1994: 92). Similar approaches such as Economic Production Quantity (EPQ) and Economic Order Interval (EOI) have been developed to achieve the same results in slightly different environments (Tersine, 1994: 121-140). Other techniques have also been developed to more accurately account for variations in demand, including Lot-For-Lot Ordering, Periodic Order Quantity, Wagner-Whitin Algorithm, Silver-Meal Algorithm, Least Unit Cost, Part-Period Algorithm, and Material Requirements Planning (Tersine, 1994: 178). A more detailed look at these alternative approaches is presented in the following section.

Independent Demand Systems (EOQ)

Economic Order Quantity Overview

Perhaps the most commonly used approach to inventory management is use of the Economic Order Quantity (EOQ) model, which aims to minimize the total inventory cost. The classic inventory model, depicting the economic order quantity Q* and the reorder point B, is shown in Figure 1 below.

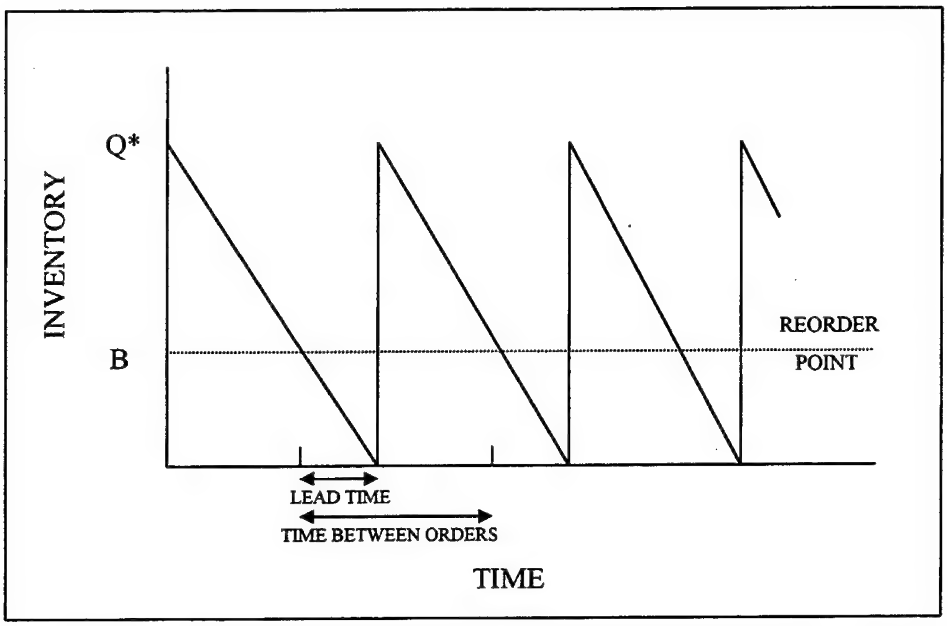


Figure 3: Classical Inventory Model (Adapted from Tersine, 1994: 93)

The economic order quantity Q* is derived from the total inventory cost equation, made up of three components: purchase cost, order cost, and holding cost (Tersine, 1994: 92). The purchase cost is calculated by multiplying the annual demand in units times the unit purchase cost, given by formula 1 below:

$$PurchaseCost = P \times R \qquad (1)$$

Where: P = Unit Purchase Cost
R = Annual Demand in Units

Order cost is calculated by multiplying the cost per order by the number of orders, where the number of orders is equal to the annual demand (R) divided by the order quantity per order:

$$OrderCost = \frac{C \times R}{Q} \tag{2}$$

Where: C = Cost Per Order
Q = Order Quantity Per Order

Finally, the holding cost is calculated by multiplying the holding cost per unit by the average number of units in the inventory. Average inventory is half the order quantity, while the holding cost is a percentage of the purchase cost:

$$HoldingCost = (P \times F) \times \frac{Q}{2} \tag{3}$$

Where: F = Annual Holding Cost Fraction

Combining equations (1), (2), and (3), the total inventory cost becomes:

$$TC(Q) = PR + \frac{CR}{Q} + \frac{PFQ}{2} \tag{4}$$

The total cost in equation (4) can now be minimized by taking the first derivative with respect to Q and setting it equal to zero:

$$\frac{dTC(Q)}{dQ} = \frac{H}{2} - \frac{CR}{Q^2} = 0 \tag{5}$$

Finally, solving for Q in equation (5) yields the "economic order quantity" Q*:

$$Q^* = \sqrt{\frac{2CR}{PF}} \tag{6}$$

In theory, then, the economic order quantity Q* represents the ideal lot size to minimize the total cost of holding and ordering inventory. This minimum is depicted in Figure 2 below, and also happens to coincide with the point at which holding cost equals ordering cost. It should

be noted that since unit purchase cost is not a function of quantity, this term is dropped from the equation upon taking the first derivative.

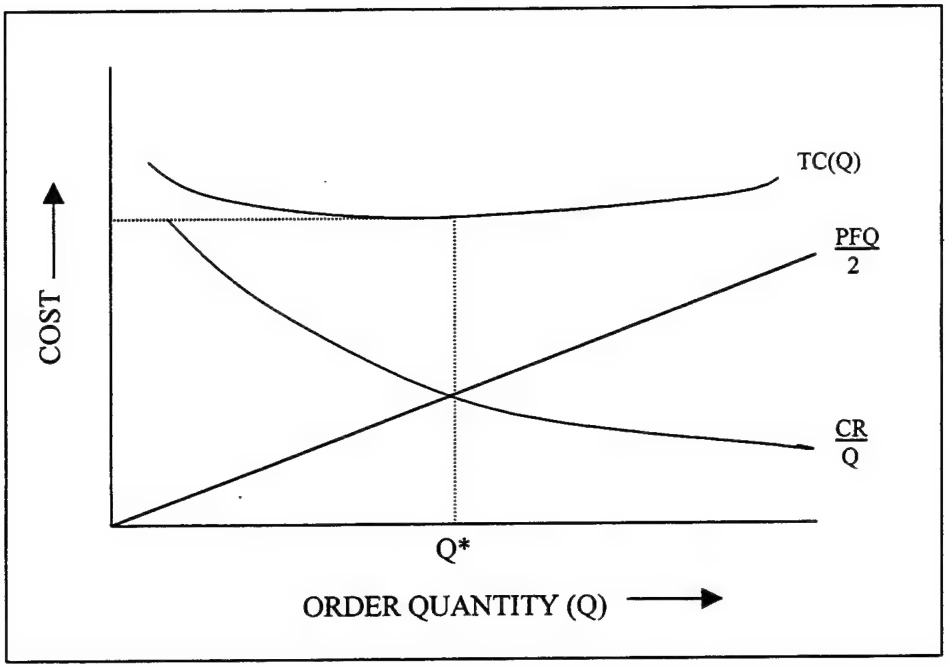


Figure 4: Annual Inventory Costs (Adapted from Tersine, 1994: 94)

The model is dependent on seven assumptions, however, some of which warrant further discussion. The assumptions of the EOQ model are as follows (Tersine, 1994: 205):

1. The demand is known, uniform, and continuous.
2. The production rate is known, uniform, and continuous.
3. The lead time is known and constant.
4. The order/setup cost is known and constant.
5. The holding cost is known, constant, and linear.
6. There are no resource limitations (dollar limits or space limits).
7. Stockouts are usually not permitted (infinite stockout cost).
8. The cost of the inventory analysis is negligible.

Although seemingly very liberal, the deterministic assumptions of the classic EOQ model usually hold even when a measure of stochasticity is introduced. This is generally referred to as the "robustness" of the model, which indicates that the optimal solution is relatively insensitive to changes in the model's parameters. This can be seen graphically in Figure 2 as the flatness of the

total cost curve to the left and right of the optimal solution Q*. Simply put, even if the assumptions do not hold, as is often the case, the total cost will not change dramatically from the optimal solution (Tersine, 1994: 102).

Given the robustness of the EOQ model, it would appear to be an excellent tool in determining order quantities and stock levels. In fact, in many instances the EOQ model does perform as intended. Demand and lead time uncertainty can usually be tempered by the use of safety stock, which "buffers" the system against potential stockouts due to variability (Tersine, 1994: 206). Such safety stock can be calculated to provide a desired level of service. This extra inventory comes with an additional cost, however, and raises the issue of how far the assumptions can be stretched before the effectiveness of the model erodes. Figure 3 illustrates a hypothetical case where the lead time for the final order exceeds the average ("late delivery"), and working stock levels become insufficient to satisfy requirements. In this case, safety stock is able to satisfy these requirements, thereby precluding a work stoppage.

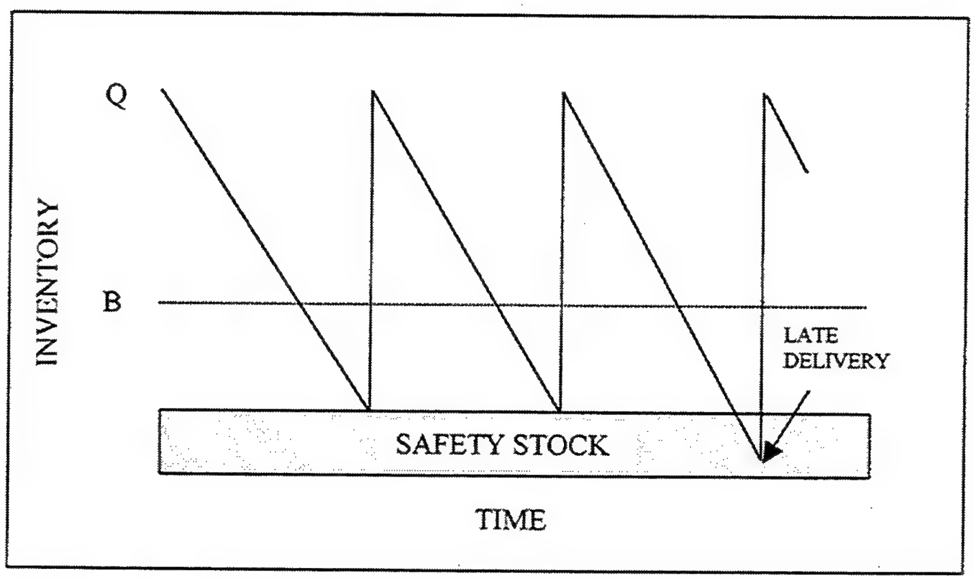


Figure 5: Classical Inventory Model with Safety Stock (Adapted from Tersine, 1994: 539)

EOQ in the Department of Defense

In the Department of Defense, the EOQ model's performance has been subjected to a great deal of scrutiny in recent years. The list of General Accounting Office (GAO) reports on the subject is formidable in and of itself. Beginning in the late 1980s, GAO began monitoring DoD stockage policies at the request of the House of Representatives Committee on Government Reform and Oversight and the Senate Committee on Governmental Affairs. The topic was soon elevated to the GAO's "High Risk Series" because of its budgetary implications. In a report issued in 1992, the GAO stated that, although the DoD had reduced its inventory from $92.5 billion to $77.5 billion, about one-half of the remaining $77.5 billion was still excess (GAO, 1995b: 5). In the same report, recommendations were made that the DoD change its culture, increase use of commercial practices, revise its performance measures to match its new focus, and begin to integrate improved computer systems to better control inventory (GAO, 1995b: 9).

Following up on the 1992 suggestions, GAO has continued to emphasize the need for the use of commercial practices, underscoring its skepticism in DoD's ability to efficiently manage inventory. In 1995, it published the results of a study indicating that lead times were inaccurate in DLA's data bases, resulting in a $13 billion growth in lead time requirements during the 1980s (GAO, 1994: 1). A 1996 report cited practices being employed by commercial airlines, including Just-In-Time (JIT), advanced information systems, and state-of-the-art repair facilities (GAO, 1996a: 1). It recommended that the DoD look into the use of Third-Party Logistics, supplier distribution centers ("supplier parks"), repair cycle reductions, and upgraded facilities to reduce inventory (GAO, 1996a: 6). Apparently frustrated with the lack of progress, the GAO published two reports in 1997 that proposed short-term solutions to optimize inventory management using the existing infrastructure. One of the reports merely emphasized maximizing the efficiency of existing systems (GAO, 1997b: 4), while aiming in the long-term to provide inventory managers with "automated, integrated accounting and management systems" (GAO, 1997b: 11). The

second recommended developing new indicators (metrics) that encourage excess inventory reduction, the use of efficient and effective inventory management practices, and increased training of personnel (GAO, 1997a: 10).

The GAO has been particularly critical of the Defense Logistics Agency (DLA) in the area of inventory management. DLA has been charged with the responsibility of managing the majority of consumable items for all defense activities, and as such is the primary wholesale supplier for these items. As of 1997, DLA managed over 4 million items with an inventory value of about $11.1 billion (GAO, 1997c: 4). Although the GAO has stopped short of making recommendations regarding the actual methodology to be used, it has made it painfully clear that changes need to be made. These changes have been slow in coming. To begin to solve the problem of inventory management, and at GAO's urging, DLA has instituted some commercial practices with success in managing its medical and food supplies. These items constitute only about 3% of total consumables at DLA, however, so the overall effect has been minimal (GAO, 1997c: 7).

One of the most pervasive problems DLA faces in consumable item management relates to the sheer vastness of its operations and the diverse missions of its customers. In a system of this magnitude, the inevitable erroneous data in the system can alone present a major problem in requirements determination. For example, GAO reported in 1996 that the Air Force had been excluding on-hand balances from requirements and budget computations, resulting in a $72 million overstatement of requirements in fiscal year 1996 (GAO, 1996b: 4). Even after adjustment of the budget submission to reflect the overstatement, the GAO found that 64% of Air Force and Navy items it sampled were either overstated or understated, for a combined absolute value of over $35 million (GAO, 1996b: 5). In the same report, it was noted that requirements discrepancies were due to incorrect replacement rates, demand rates, planned program

requirements, due-out quantities, lead times, repair costs, and asset quantities on-hand and on-order (GAO, 1996b: 5).

Given the apparent ineffectiveness and inefficiency of the EOQ model for DLA's consumable item management, it is now appropriate to briefly discuss the model it uses. DLA uses a variation of Wilson's classic EOQ model discussed earlier. The major difference in DLA's version of the model is its replacement of the annual demand component ("R" in equation (6)) by a Quarterly Forecast Demand (QFD) (Goulet and Rollman, 1996: 27). Substituting the QFD into equation (6) yields the DLA EOQ formula below:

$$EOQ_{DLA} = \sqrt{\frac{2(4QFD)C}{PF}} \tag{7}$$

To simplify calculations, DLA also uses a "T Factor" to replace the constants in equation (7), yielding the following (Goulet and Rollman, 1996: 28):

$$EOQ_{DLA} = T\sqrt{\frac{QFD}{P}} \tag{8}$$

$$\text{where } T = 2\sqrt{\frac{2C}{F}}$$

The DoD's inventory problems can hardly be blamed on mismanagement at DLA. The EOQ model is popular not only for its robustness, but also for its relative simplicity. In an operation the size of the DoD, simplicity is a very real necessity. As computing power has increased exponentially over the past two decades, however, it is certainly time to begin employing more powerful models in inventory management. There is no shortage of research to support this effort. Numerous studies, both in and outside of the DoD, have attempted to test the

EOQ's ability to perform under various environmental conditions. Most of the research has focused on the effects of increasing levels of variability and uncertainty in demand or lead time, or both.

<u>Studies of EOQ Performance</u>

Axsater and Rosling compared the EOQ model to Material Requirements Planning (MRP) in a multi-level production environment and found MRP to be superior to simple reorder point policies in terms of system control. They added that simple reorder point (ROP) policies like the EOQ may still be advantageous in some instances, however, due to its low administrative cost and simplicity (Axsater and Rosling, 1994: 411). Jacobs and Whybark similarly compared MRP and ROP for different levels of demand variability, commonly referred to as "lumpiness" (Jacobs and Whybark, 1992: 335). Specifically, they asked the question of "how bad must it be" before the preference for MRP over ROP would be reversed (Jacobs and Whybark, 1992: 339). The answer provided further evidence that ROP techniques like the EOQ model fell short on performance: "A very perverse environment is needed before the preference [for ROP] can be argued on inventory efficiency grounds" (Jacobs and Whybark, 1992: 341). Grasso and Taylor looked at the effects of lead time uncertainty on system performance in a simulation study of several common lot-sizing techniques, including EOQ. Based on the results of their study, they emphatically recommended using anything but EOQ when lead time uncertainty is present (Grasso and Taylor, 1984: 496).

Similar results can be seen in DoD research. Long and Engberson studied the effect of violations of the constant and continuous demand assumption on DLA's EOQ model. One problem they illustrate is that of multiple users of common items, and its effect on the lumpiness of demand. For a given item, some customers may order frequently, while others order infrequently or erratically. When these diverse requirements come together at DLA, despite the efforts of individual customers, lumpy demand data becomes the norm (Long and Engberson,

1994: 73). They recommend further research into alternative lot-sizing techniques that consider lead time, annual demand, and demand patterns, and point to Distribution Requirements Planning (DRP) as a model with potential (Long and Engberson, 1994: 74).

A similar study by Berry and Tatge looked at the effect of lumpy demand on inventory levels and total variable cost. The results indicate that DLA's EOQ model is not robust enough to handle the degree of lumpiness commonly found in DoD items (Berry and Tatge, 1995: 5-2). They went on to test the Silver-Meal (S-M) algorithm as an alternative to EOQ, and found it superior in terms of both inventory levels and total variable cost (Berry and Tatge, 1995: 5-2). Goulet and Rollman followed up the Berry and Tatge study by simulating the performance of DLA's EOQ model, S-M, and the Periodic Order Quantity (POQ) algorithm. This study used three of DLA's ten Selective Management Category Codes (SMCCs), representing three diverse levels of demand. For low demand items with less than 4 demands per year, they found the DLA EOQ model to outperform the others. For medium demand items with 4 to 149 demands per year, however, POQ and S-M outperformed EOQ (Goulet and Rollman, 1996: 65-67).

Several DoD studies have focused more on the short-term problem of optimizing the EOQ model, versus adopting a new philosophy altogether. In 1990, Hanks reported that 2% of DLA-managed items accounted for some 92% of the total number of outstanding unit backorders (Hanks, 1990: 4-2). This led him to the conclusion that the backorder problem was rooted not in expected backorders but in unexpected backorders (Hanks, 1990: 4-3). Again, the EOQ model's inability to deal with a changing environment was highlighted. His suggestion to deal with the aforementioned problem of multiple users of common items, and its associated lumpy demand, was simple: DLA should classify items according to weapons system, rather than by item type (Hanks, 1990: 3-2). Using this approach, his study showed a 2/3 reduction in safety level investment, with a corresponding 25% reduction in expected backorders (Hanks, 1990: 3-3).

Hanks later recommended maintaining higher safety levels for consumable line replacement units (LRUs), with lower levels for other consumable parts (Hanks, 1993: A-1).

Other studies have taken a similar approach in attempting to maximize the effectiveness of the existing EOQ model. Bachman and Kruse investigated the possibility of using operational measures to forecast demands in lieu of estimates based on historical data. Unfortunately, they found little correlation between such operational measures as densities (number of systems), flying hours, and overhauls and actual demands (Bachman and Kruse, 1994: Page #?). Their recommendation then turned to optimizing existing techniques by using single exponential smoothing of historical data, with a smaller smoothing constant α than DLA was using at the time (Bachman and Kruse, 1994: 1-5). A similar study simulated six forecasting techniques, four using popular exponential smoothing techniques and two using daily demand rates (Blazer, et al., 1984: 3). The study found that DLA's system was adequate in estimating average demand, but safety level calculations were poor because of high demand variation in 40% of the Air Force's EOQ items (Blazer, et al., 1984: 15).

The two most important performance measures of an inventory model are cost and customer service. In most DoD organizations, cost is an ongoing concern because of budget considerations. Customer service can be defined in many ways, but from the point of view of the maintainer of a weapon system, customer service is generally a function of supply availability. As such, a good inventory system should aim to reduce backorders within budgetary constraints. Dynamics Research Corporation (DRC), under contract with the Oklahoma City Air Logistics Center (OC-ALC), studied 724 backorders in 1996 to determine their root causes. Of these, 205 were considered "action items," while the remainder were randomly selected backorders. Action items are backorders that are currently affecting production, and as such are receiving special management attention. However, most backorders that are not currently considered action items have the potential to delay production at any time in the process. At the time of the baseline, 52

of the 93 engines in work were in work-stoppage status awaiting parts (AWP) (DRC, 1997: 2). The report concluded that 54% of the backorders could be tied to lumpy demand patterns (DRC, 1997: 6). Many reasons were cited for the lumpiness in demand (DRC, 1997: 3):

- Implementation of on-condition maintenance (OCM) policies under two-level maintenance (2LM) concept, where emphasis shifted to fixing only those parts that were broken instead of the traditional complete overhaul. This policy exacerbates the instability of demand patterns.

- Shorter turnaround requirements driving more replacements in lieu of repairs.

- Transfer of parts from field to depot as a result of 2LM temporarily created a parts overage, making historical demand data inaccurate.

- Initial Spares Support Lists (ISSLs) for new engines were overstated in many cases, creating a similar demand lag as with the parts transfer mentioned above.

The DRC study once again raised the notion that the traditional EOQ approach was inappropriate for at least some of DoD's operations.

Effects of Violations of Known Cost Assumptions

Like violations of the demand, lead time, and production assumptions, violations of the known cost assumptions can have a significant impact on the total cost associated with using the EOQ model. Although relatively little research has been conducted in this area, a simple sensitivity analysis can show the effects of errors in holding and ordering cost values. One such study, conducted by Morten Meinich at the Naval Postgraduate School, used data from the Ships Parts Control Center (SPCC) in Mechanicsburg, Pennsylvania to create a spreadsheet simulation. The simulation was then used to test the effects of using an average cost across all items in lieu of actual costs for each item. For example, Meinich reported that the Navy uses the total variable cost associated with ordering for a particular year divided by the total number of line items to calculate the average ordering cost. The first interesting observation from the study was that the average ordering cost used in EOQ calculations varied from about $82 per line item in 1980 to a

high of about $390 in 1988 (Meinich, 1988: 65). This observation alone seriously degrades the credibility of the "known and constant ordering cost" assumption inherent in the EOQ model.

Meinich then went on to perform a regression analysis to determine if better estimators of ordering and holding costs could be found. Several independent variables were tested with little success. He found no significant correlation between costs and such variables as number of line items and unit purchase costs, and his tests using combinations of independent variables likewise failed to prove significant (Meinich, 1988: 78). In fact, when the total number of line items was used as the independent variable, representing the level of activity for a particular year, an unexpected inverse relationship was discovered. In years with a high level of activity, total ordering costs were significantly lower than in years with low activity (Meinich, 1988: 79-80).

Meinich's simulation objective was to estimate the "extra cost [X cost] incurred due to the lack of knowledge of the (true) holding cost rate" (Meinich, 1988: 73). When uncertainty exists in estimating the holding cost rate, two outcomes are possible. First, the holding cost could be overestimated, resulting in an EOQ that is smaller than optimal. In terms of costs, the ordering cost will increase at a greater rate than the holding cost, driving the total variable cost up. Although the cost increase is relatively small due to the robustness of the EOQ model, this case would result in a lower inventory level than needed (Meinich, 1988: 74). By inference, this would lead to an increase in backorders and a decrease in readiness. Considering the opposite, if the holding cost were underestimated, the EOQ would be greater than optimal and too much stock would be carried. Like in the first case, the total variable cost would increase slightly. In this case, however, excess inventory would result (Meinich, 1988: 74).

To compute a baseline against which to compare the cost increases, Meinich first used the EOQ assumption of a known and constant holding cost of 23 percent. The simulation then used seven different holding cost distributions to estimate the X-cost associated with holding cost uncertainty. Average X-costs increased between 0.41 to 4.27 percent from the baseline (Meinich,

1988: 86). About 85 percent of the values were relatively close, however, leading him to recommend a Pareto approach to isolating the significant few for management action (Meinich, 1988: 87).

Meinich was not alone in his skepticism of defense cost estimates. The General Accounting Office investigated the cost accounting practices of the DoD throughout the implementation period of the Defense Business Operating Fund (DBOF). DBOF was created to consolidate the nine industrial and stock funds operated within the DoD and the individual services, as well as several other related funds. It provides for, among other things, the overhaul of major weapon systems and the sale of vital inventory items (GAO, 1995a: 3). A 1995 GAO report reiterated its previous claims that the Fund was not achieving its objectives because of inadequate policies, inaccurate financial reports, and fragmented cost accounting systems (GAO, 1995a: 1). The latter two are particularly relevant to the current discussion, since they confirm Meinich's finding that the Air Force and other DoD agencies are seriously violating one of the fundamental assumptions of the EOQ model. Specifically, the GAO report stated that "about 80 disparate and unlinked systems are producing accounting data" (GAO, 1995a: 7). They add that "systems that produce credible cost data are essential for the successful operations of the Fund...[and are] also critical in order to develop systematic means to reduce the cost of operations" (GAO, 1995a: 7).

In light of the research presented above, why does the DoD continue to use the EOQ model for inventory requirements? One reason is its simplicity. As previously mentioned, the EOQ model is computationally simple and is insensitive to relatively large parameter errors. Another possible explanation is that the growing defense budget of the early 1980s made unusually large safety stocks possible. Even if the EOQ model itself is inappropriate for DoD consumables, high levels of safety stock could mask even large degrees of lumpiness and, likewise, model ineffectiveness. In fact, the start of GAO's investigation of DoD inventory

practices coincided with the start of declining defense spending. It was not until a time of scarce funding that major inventory problems began to emerge and warrant congressional oversight. Finally, organizational inertia can probably accept part of the blame. The simple reality is that in an organization the size of the Department of Defense or the Air Force, change comes very slowly. Often policy changes "die on the vine" with each passing change of command. As time passes, we can only hope that current inventory knowledge will find its way into lasting policy changes.

Discrete Demand Systems

Because of the EOQ's inability to deal with large variations in demand, a variety of dynamic lot-sizing techniques have been developed that are more suitable to "discrete demand." Discrete demand is characterized by variations over time, as opposed to the smooth continuous demand assumed by the EOQ model (Tersine, 1994: 178). This section gives a brief overview of some of these techniques. The discussion serves two purposes in light of the current research. First, experimentation using these techniques has generally shown that most of them outperform the EOQ model under variable conditions (Grasso and Taylor, 1984; Lee and Adam, 1986; Robillard, 1994; Berry and Tatge, 1995; Goulet and Rollman, 1996), thus lending further evidence that the EOQ should be avoided in many environments. Second, MRP systems can use any of the lot-sizing techniques described in this paper, to include the EOQ. A great deal of MRP research has concentrated at least partly on the selection of an appropriate lot-sizing technique for a given environment (Kropp et al., 1983; Blackburn et al., 1986; Brennan and Gupta, 1993; Zhao et al., 1995; Goulet and Rollman, 1996), so a basic understanding is necessary as a foundation for the MRP discussion. Like the EOQ model, the lot-sizing techniques described in this section are based on a number of assumptions (Tersine, 1994: 179):

1. The demand is known but varies from one period to another.
2. The planning horizon is finite and composed of several time periods of equal length.
3. Lot sizes include one or more integer time periods of demand taken in the same sequence as the chronology of the planning horizon.
4. No orders are scheduled to be received at the beginning of a period in which demand is zero.
5. Lead time is zero.
6. Replenishments arrive all at once and at the beginning of a period.
7. The entire requirements for each period are available at the beginning of that period. No shortages or stockouts are permitted.
8. Items required in a period are withdrawn from inventory at the beginning of the period, making holding cost applicable only to the ending balance.
9. All items are treated independently of other items.
10. Unit cost is constant (no quantity discounts).
11. Inventory costs and lead times are known and constant.
12. Demand beyond the planning horizon is ignored.

Although greater in number than the EOQ assumptions, the assumptions listed above are generally much less liberal. Two notable exceptions are the known demand and known and constant lead time assumptions. Although the techniques described below allow for varying demand, the level of uncertainty in demand also plays a large role in the success or failure of a system (Brennan and Gupta, 1993: 1706). Beyond these two exceptions, however, the list of assumptions can be regarded as reasonable.

Lot-For-Lot Ordering (LFL)

Lot-For-Lot Ordering, as its name implies, involves ordering the exact amount needed for each individual production run or period. In theory, this approach will have the effect of eliminating holding cost, since materials are ordered and consumed only as needed. LFL

therefore performs very well when ordering costs are low and unit purchase cost is high, as well as in assembly line production environments (Tersine, 1994: 180). Brennan and Gupta found LFL to be associated with high costs in most cases (Brennan and Gupta, 1993: 1700). Blackburn, Kropp, and McMillen produced similar results, with LFL being associated with poor cost performance and an inability to effectively dampen system nervousness (Blackburn et al., 1986: 419). Lee and Adam also found LFL to be among the poorest lot-sizing techniques with respect to performance and cost when subjected to forecast errors (Lee and Adam, 1986: 1200). In contrast, Grasso and Taylor found LFL to perform well when lead time is characterized by a uniform discrete distribution (Grasso and Taylor, 1984: 496). Debodt and Van Wassenhove noted that LFL starts out as a high cost option, but as forecast errors grow its performance remains relatively constant, thus closing the gap with other techniques (Debodt and Van Wassenhove, 1983: 352).

Periodic Order Quantity (POQ)

The POQ lot-sizing technique is a variation of the EOQ model that converts the economic order quantity (EOQ) to an economic order interval (EOI) using the following formula:

$$EOI = \frac{EOQ}{\overline{R}} = \sqrt{\frac{2C}{\overline{R}PF}} \qquad (9)$$

Where: $\overline{R}$ = Average Demand Rate per Period

The EOI calculated from equation (9) is then rounded to the nearest integer value, and that number of periods becomes the basis for ordering quantities (Tersine, 1994: 180). The advantage of using POQ over EOQ is that lot sizes are allowed to vary, but combining low-demand periods into larger orders becomes difficult (Tersine, 1994: 181). Brennan and Gupta found POQ's cost performance to be better than EOQ's, but it was still outperformed by other more sophisticated lot-sizing techniques (Brennan and Gupta, 1993: 1700). Grasso and Taylor found POQ to outperform EOQ under lead time uncertainty (Grasso and Taylor, 1984: 496). Lee and Adam

also found POQ to outperform EOQ, LFL, and part-period balancing (PPB) under conditions of forecast error (Lee and Adam, 1986: 1200).

Wagner-Whitin Algorithm (W-W)

The W-W algorithm is an iterative procedure to minimize controllable costs, and is often used in research as an optimal solution against which to compare simpler techniques. Although usually outperformed in practice (Brennan and Gupta, 1993; Zhao et al., 1995;), the W-W algorithm at least provides a theoretical baseline. In essence, W-W first derives a total variable cost matrix, which is used to create a total variable cost alternatives matrix. The latter is then used to derive an optimum ordering schedule (Tersine, 1994: 185-186). The total variable cost equation used to formulate the first matrix is as follows (Tersine, 1994: 182):

$$Z_{ce} = C + hP\sum_{i=c}^{e}(Q_{ce} - Q_{ci}) \qquad \text{for } 1 \le c \le e \le N \tag{10}$$

Where C = Ordering Cost per Order
H = Holding Cost Fraction per Period
P = Unit Purchase Cost
$Q_{ce} = \sum_{k=c}^{e} R_k$
R_k = Demand Rate in Period k

Zhao, Goodale and Lee report that several attempts have been made to incorporate the cost of schedule changes into equation (10), and in their own study show that addition of such a "change cost" can improve the cost performance of most lot-sizing techniques (Zhao et al., 1995: 2273).

Silver-Meal Algorithm (S-M)

Silver and Meal developed a heuristic lot-sizing algorithm which attempts to find the optimal number of periods in a replenishment order based on the lowest cost for that period (least period cost). The algorithm involves a marginal analysis in which additional periods are added to an order until the cost per period first increases, at which point that order is locked in. This procedure is then repeated for subsequent periods until the entire planning horizon is exhausted

(Tersine, 1994: 186). Like other algorithms, S-M uses a cost equation as its foundation (Tersine, 1994: 186):

$$\frac{TRC(T)}{T} = \frac{C + TotalHoldingCostsToTheEndOfPeriodT}{T}$$

$$= \frac{C + Ph\sum_{k=1}^{T}(k-1)R_k}{T} \tag{11}$$

Where: C = Ordering Cost per Order
h = Holding Cost Fraction per Period
P = Unit Purchase Cost
Ph = Holding Cost per Period
TRC(T) = Total Relevant Cost over T periods
T = Time supply of the Replenishment in periods
R_k = Demand Rate in Period k

Although Silver-Meal does not guarantee the optimal solution like W-W, it nevertheless provides a close approximation that is usually within one percent. Computationally it is much simpler, however, and it often outperforms W-W when a rolling horizon is used. Tersine notes two situations where S-M performs poorly (Tersine, 1994: 187):

1. When the demand rate decreases rapidly with time over several periods
2. When there are a large number of periods with zero demand

The S-M algorithm has performed well in experimental research. Zhao, Goodale, and Lee found a modified version of S-M, which included a change cost component, to be the best of the lot-sizing techniques they tested (Zhao et al., 1995: 2273), as did Kropp, Carlson, and Jucker (Kropp et al., 1983: 168). Robillard developed a modified S-M heuristic which incorporated a time-varying mean to account for known future trends, and found it to reduce excess, wait times, and total costs (Robillard, 1994: 99). Goulet and Rollman, in a defense-specific study, found S-M to outperform DLA's EOQ model for medium demand items, although it was in turn outperformed by the POQ technique (Goulet and Rollman, 1996: 67). Brennan and Gupta also found S-M to be one of the lowest cost lot-sizing techniques (Brennan and Gupta, 1993: 1700).

Least Unit Cost (LUC)

A variation of the Silver-Meal algorithm, the LUC heuristic averages costs over units instead of averaging costs over periods. Like S-M, LUC uses a marginal analysis approach to increase the number of periods in a replenishment order until the average cost per unit first increases (Tersine, 1994: 188). The total relevant cost formula thus becomes (Tersine, 1994: 188-189):

$$\frac{TRC(T)}{\sum_{k=1}^{T} R_k} = \frac{C + TotalHandlingCostToTheEndOfPeriodT}{\sum_{k=1}^{T} R_k}$$

$$= \frac{C + Ph\sum_{k=1}^{T}(k-1)R_k}{\sum_{k=1}^{T} R_k} \qquad (12)$$

Although Silver-Meal is more popularly used in research studies, Brennan and Gupta tested both S-M and LUC and found that the two performed comparably with respect to cost (Brennan and Gupta, 1993: 1700).

Part-Period Algorithm (PPA)

The part-period algorithm (PPA), also referred to as part-period balancing (PPB), is a heuristic that aims to choose the number of periods to be included in a replenishment order by balancing ordering and holding costs. Similar to S-M and LUC, it iteratively adds periods until the accumulated holding costs are less than or equal to the ordering cost (Tersine, 1994: 190). The following formula is applied (Tersine, 1994: 190):

$$\sum_{k=1}^{T}(k-1)Rk = \frac{C}{Ph} \qquad (13)$$

Where: C = Ordering Cost per Order
h = Holding Cost Fraction per Part-Period
Ph = Holding Cost per Part-Period
C/Ph = EPP = Economic Part-Period

$$\sum_{k=1}^{T}(k-1)R_k = \text{APP} = \text{Accumulated Part-Periods}$$

Research using the PPA has shown variable results. Brennan and Gupta found the PPA to perform well with respect to cost, approaching the performance level of S-M (Brennan and Gupta, 1993: 1700). Kropp, Carlson, and Jucker saw conflicting results, noting that their change-cost modified PPA performed "poorly and erratically" (Kropp et al., 1983: 156). Lee and Adam perhaps explained this inconsistent performance best when they noted that the relative performances of PPA, EOQ, and POQ were contingent upon the MRP structures and the degree of forecast error levels employed (Lee and Adam, 1986: 1200).

Dependent Demand Systems: Material Requirements Planning

In contrast to the EOQ and other independent demand systems, which assume demand for each individual item is independent of demand for any other item, Material Requirements Planning (MRP) theory assumes that only end-item demand is independent. All demand at lower echelons is then dependent on the end-item demand (Tersine, 1994: 337). Using an Air Force engine example, the engine experiences independent demand, while the demand for a turbine blade to fix the engine is dependent on the engine demand. With this mathematical relationship, MRP systems attempt to calculate dependent demand based on end-item production requirements.

MRP systems utilize three major inputs in their calculations of requirements: the master production schedule (MPS), the bill of materials (BOM), and inventory status records (Tersine, 1994: 338). The master production schedule summarizes forecasted or planned end-item production, and provides the foundation for all subsequent requirements calculations (Tersine, 1994: 338). As such, it is regarded as the single most important input to an MRP system (Barret and LaForge, 1991: 571). The Air Force equivalent of the MPS is the D041 Recoverable

Consumption Item Requirements System, which aggregates Air Force-wide requirements for each recoverable item into overall Air Logistic Center (ALC) maintenance targets.

The bill of materials (BOM) is a hierarchical record of the product structure that identifies the types and amounts of raw materials, sub-assemblies, and components that are required for end-item production. In addition to inventory information, the BOM stores information regarding the sequence of production steps required to complete an end-item (Tersine, 1994: 340). By using the MPS and BOM together, simple calculations determine the material requirements for production. The third major input to an MRP system, inventory status records, is used to determine the number of items currently on-hand or on-order. This balance is then compared with the requirements calculated from the MPS and BOM, and shortfalls are marked for inventory action. In addition to the inventory status, the records contain lead time data fields which are used to offset orders so that they arrive precisely when needed (Tersine, 1994: 340). In this way, MRP systems aim to minimize inventory and maximize availability. Figure 4 illustrates the inputs and outputs characteristic of an MRP system.

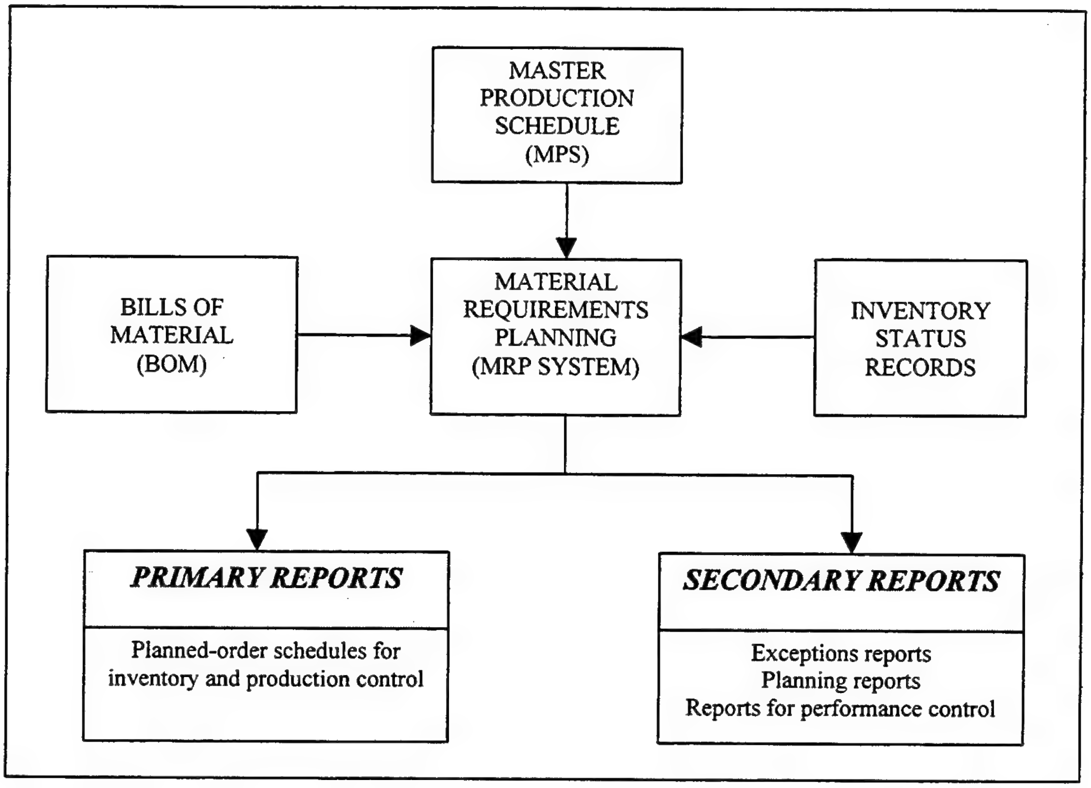


Figure 6: Inputs to and Reports Generated by an MRP System
(Adapted from Chase and Aquilano, 1992: 704)

Since its development in the late 1960s, MRP has become increasingly popular among manufacturing firms. Anderson and Schroeder conducted a survey in the early 1980s in which 65% of the respondents reported using an MRP system (Anderson et al., 1982: 53). The same study found the highest use in job shop and assembly line operations, constituting approximately 38.8% and 29.7% of total MRP users, respectively (Anderson et al., 1982: 56). The following average characteristics illustrate the general type of firm employing MRP:

Table 1: Comparison of MRP and Non-MRP Firms (Anderson et al., 1982: 57)

CHARACTERISTIC	**MRP Firm Averages**	**Non-MRP Firm Averages**
Number of End Items	3,002	3,000
Number of Parts/Components	25,782	12,000
Levels in Bill of Materials	6.9	5.84
Number of Employees	1,064	578
Number of Production and Inventory Control Employees	19	12.5

With the exponential increase in firms using MRP came a corresponding increase in MRP research. Although MRP theory is based on direct mathematical relationships, its success is contingent upon the environment in which it is used. This is due to the fact that the foundation of the system is the master production schedule, and instability in the same leads to increasing degrees of suboptimal performance. If the MPS is relatively stable and easy to predict, MRP performs extremely well. If the MPS is dynamic and variable, however, "system nervousness" is created with a negative impact on MRP's effectiveness.

System Nervousness

System nervousness can be defined as significant changes to MRP plans resulting from even small changes to higher level plans or the MPS (Vollmann et al., 1992: 466). In MRP systems, nervousness creates an environment of changing requirements, which makes planning calculations difficult. It manifests itself in the forms of both material shortages and excess inventory, eroding many of the benefits of the system (Chalmet et al., 1985: 244). System nervousness is primarily the result of uncertainty and variation in production, lead times, and demand (Vollmann et al., 1992: 466). The three sources are interconnected, however, so that

increased variability in demand and lead times tends to increase variability and uncertainty in production (Blackburn et al., 1986: 414). A related type of nervousness in MRP systems is referred to as execution nervousness. When planning nervousness occurs, the system issues change notices in response. These change notices, if users are not properly educated in MRP theory, can stimulate "arbitrary or defensive actions" (Vollmann et al., 1992: 468). This, in turn, worsens the overall nervousness of the system. Most MRP research has focused on MRP's performance under varying levels of system nervousness, comparing it to other popular inventory systems.

Blackburn, Kropp, and Millen conducted a simulation study to determine "cost, demand, stage-structural, and length of planning horizon conditions under which different [MRP] approaches are effective." They contend that most studies have used a static/fixed planning horizon, but that in practice most firms use a "rolling horizon." They further report that research indicates that static experiments are a poor indicator of actual performance, since lot-sizing algorithms are sensitive to the horizons used (Blackburn et al., 1986: 413). As such, they varied four factors in their study to test system performance: planning horizon, lot-sizing method, cost parameters, and product structure. Using different levels of these four factors, five MRP nervousness reduction policies were tested. These included freezing the MPS, lot-for-lot ordering, use of safety stocks, using forecasts beyond the planning horizon, and incorporating a "change cost" to account for the costs associated with changing the MPS within the planned horizon (Blackburn et al., 1986: 415). The results of the study indicate that in terms of cost performance, use of a change cost and forecasting beyond the planning horizon performed equally well, followed by freezing the MPS, lot-for-lot ordering, and safety stock (Blackburn et al., 1986: 419). In terms of reducing system nervousness, freezing the MPS dominated, but the authors note that this approach is susceptible to demand uncertainty within the planning horizon. They further note that extending the planning horizon tends to dampen nervousness, as does the

use of safety stock, but the latter often requires a significant investment (Blackburn et al., 1986: 424).

Change Cost

Before exploring further into the use of change costs in research, it is appropriate to briefly explain the concept. As discussed at the beginning of this chapter, the minimization of inventory-related costs is a major objective of most inventory systems. Most models, like the EOQ for example, traditionally use holding cost and ordering cost as the two primary components. With regards to MRP, however, there is an additional "change cost" associated with changes made to the MPS within the planning period. This cost can include unexpected setup costs due to schedule changes, costs associated with expediting material orders, and additional labor costs. When minimizing total cost, therefore, it is appropriate to include the change cost component.

The use of a change cost was not a new concept at the time of the Blackburn study. Dean Kropp and Robert Carlson had been researching the subject since the late 1970s, and had published several articles supporting its use. An early study used a model based on the Wagner-Whitin algorithm under static conditions, and found that system nervousness can indeed be reduced by incorporating a change cost (Kropp and Carlson, 1984: 243). In a related study, two variations of modified Silver-Meal and one modified Part Period Balancing model were used and compared with the Wagner-Whitin algorithm (Kropp et al., 1983: 156). This time six parameters were used to test the limits of each algorithm: planning horizon, demand pattern, setup cost, change-to-setup cost ratio, patern of change-cost decline, and pattern of demand change (Kropp et al., 1983: 161). One of the modified Silver-Meal models performed extremely well, with just slightly higher total cost than the optimal Wagner-Whitin solution, and the authors point out that using the change cost adjustment can improve most lot-sizing techniques (Kropp et al., 1983:

168). They add that the modified Part Period Balancing heuristic performed "poorly and erratically" (Kropp et al., 1983: 156).

A similar study by Zhao, Goodale, and Lee investigated the effects of lot-sizing rules and freezing the MPS under demand uncertainty. They begin by illustrating that MRP nervousness is caused by, among other things, end item forecast revisions, lot-sizing rule side effects, and scheduled receipt changes (Zhao et al., 1995: 2241). In their use of different lot-sizing rules, they included "cost modified" versions of the Wagner-Whitin and Silver-Meal algorithms to account for the change costs discussed by Blackburn et al. Their results indicate that the cost modified lot-sizing rules generally lead to lower costs and lower schedule instability in multilevel MRP systems, with the cost-modified Silver-Meal outperforming the rest (Zhao et al., 1995: 2273). With respect to freezing the MPS, the authors found a significant degree of interaction between the lot-sizing rule and freezing parameters, leading to their conclusion that freezing parameters should be selected carefully with full consideration of the lot-sizing rule being used (Zhao et al., 1995: 2273).

Replanning Frequencies

Several studies have also investigated the effects of replanning frequencies on MRP performance. Replanning is simply the recalculation of requirements by the MRP system, and is generally classified as one of two types: regenerative and net change. In regenerative systems, the entire plan is recalculated on a periodic basis. In contrast, net change systems use only partial explosions based on additions and deletions to the MPS since the last plan was calculated (Tersine, 1994: 366-367). Stable environments generally favor the use of regenerative systems, while changing environments favor the use of net change systems (Tersine, 1994: 367). In general, the appropriate replanning frequency depends on the firm, the products, and the operations involved (Vollmann et al., 1992: 30). Among firms using MRP systems, it appears that most use regenerative systems with either weekly or monthly replanning. Specifically, in

1982 nearly 70% of MRP users used regenerative systems, with about the same percentage replanning weekly. An additional 12.5% were replanning on a monthly basis (Anderson et al., 1982: 61).

Yano and Carlson looked at the interaction between replanning frequency and safety stock in MRP systems, using fill rate and total cost as performance measures. Their model was kept simple, with fixed lead times and stable supply, varying only the demand (Yano and Carlson, 1987: 222). They found that fixed schedules are more economical, assuming moderate forecast errors, and recommended that frequent rescheduling be done with caution (Yano and Carlson, 1987: 230). With regard to safety stock, the results indicated that end item safety stock would not necessarily increase service level, while component safety stock was more successful to this end. Component safety stock also seemed to have the increased benefit of reduced setup costs (Yano and Carlson, 1987: 230).

Barrett and LaForge conducted a simulation study that looked at six different replanning frequencies under different environments. The model used a "probability of change" to generate demand changes on an hourly basis, thus creating a range of environmental volatility (Barrett and LaForge, 1991: 572). All ordering was done using the lot-for-lot lot-sizing technique (Barrett and LaForge, 1991: 573). The results of the study indicate that more frequent replanning leads to higher service levels, but also to higher inventory levels and greater system nervousness (Barrett and LaForge, 1991: 574). Although limited in scope by the use of only one lot-sizing technique, the study confirmed intuition on the subject of replanning frequencies: that the additional cost of frequent replanning eventually leads to diminishing returns.

Other MRP Research

Axsater and Rosling took an analytic approach to the MRP problem, comparing MRP and ROP policies according to their mathematical formulations. They showed that MRP systems can be made to approximate ROP in terms of order points and quantities, thus providing at least the

same performance. In terms of system control, however, they advocate MRP as the superior system. They further pointed out, however, that their study ignored the costs of implementing and administering the systems and that the high administrative costs associated with MRP systems may result in a preference for the use of ROP in some cases (Axsater and Rosling, 1994: 411).

Perhaps the most comprehensive study of the main and interaction effects within an MRP system was conducted by Brennan and Gupta. Their simulation study was the first to consider uncertainty in both demand and lead times, and used between one and eight levels of seven different factors for a total of 4,032 combinations (Brennan and Gupta, 1993: 1697). The factors and levels are summarized in Table 1 below:

Table 2: Summary of Factors and Levels (Brennan and Gupta, 1993: 1693-1697)

FACTOR	LEVELS	DESCRIPTION
Product Structure	4	Shape of inventory hierarchy (Triangular, Rect., etc.)
Product Structure Variant	2	Number of siblings at each level of hierarchy
Demand Variant	3	Relative variability in demand
Lead time Bias	7	Mix of parts arrival times (early, on-time, late)
Setup-to-Holding Cost Ratio	3	Self-explanatory
Shortage Cost	1	Stockout cost
Lot-Sizing Rule	8	EOQ, L4L, LTC, LUC, POQ, PPA, S-M, W-W

In testing for main effects, Brennan and Gupta found lead time and demand uncertainty to be significant to MRP performance. Likewise, they found that the product structure variant, product structure shape, and lot-sizing rule all significantly affected MRP performance under demand and lead time uncertainty (Brennan and Gupta, 1993: 1706). Also significant were many

of the interaction effects, the most important being the interactions between lead time uncertainty and the other six factors. The reason for its importance is that lead time uncertainty was the only factor that showed significant interaction effects with all of the other factors. This result led them to the recommendation that reduction of lead time uncertainty should be a top priority for firms employing MRP systems (Brennan and Gupta, 1993: 1706).

Closed-Loop MRP and Manufacturing Resources Planning (MRP II)

As MRP theory evolved, it soon became evident that its inability to consider production capacity was a limiting factor in its success. As a result, closed-loop MRP systems began to emerge that added a feedback loop to verify output data. The outcomes of the validation checks inherent in the feedback loop are then used to make necessary changes to the MPS and MRP systems (Chase and Aquilano, 1992: 720). The American Production and Inventory Control Society (APICS) provides the following definition for closed-loop MRP:

> A system built around material requirements planning and also including the additional planning functions of Production Planning, Master Production Scheduling, and Capacity Requirements Planning. Further, once the planning phase is complete and the plans have been accepted as realistic and attainable, the execution functions come into play. These include shop floor control functions of Input-Output measurement, detailed Scheduling and Dispatching, plus Anticipated Delay Reports from both the shop and vendors, Purchasing Follow-Up and Control, etc. The term "closed-loop" implies that not only is each of these elements included in the overall system but also that there is feedback from the execution functions so that the planning can be kept valid at all times. (APICS *Dictionary*, 1984: 4)

Thomas F. Wallace identified three important characteristics of a closed-loop MRP system that distinguish it from a traditional MRP system (Wallace, 1990: 6):

1. It is a series of functions beyond simple material requirements planning.

2. It includes tools for considering priorities and capacities, and to support planning and execution.

3. It contains a feedback loop from execution to planning functions, making changes to plans possible.

Manufacturing Resources Planning (MRP II) is an extension of MRP logic that is based on a holistic view of the organization. It not only provides the capacity determination capability of a closed-loop MRP system, but also incorporates all of a company's resources, to include manufacturing, marketing, finance, and engineering (Chase and Aquilano,1992: 722). As companies began to integrate MRP systems with capacity planning, order entry, purchasing, shop floor control, and accounting systems, MRP II soon became the next logical step in the process (Demmy and Giambrone, 1990: 8). It is regarded as a company-wide system where everyone in the organization uses the same plan, the same numbers, and the same strategies (Chase and Aquilano, 1992: 722). Additionally, MRP II systems frequently add simulation capabilities that allow the user to ask "what if" questions in the planning process (Wallace, 1990: 8). Figure 3 shows the MRP II model graphically, and also illustrates the evolution from MRP to closed-loop MRP to MRP II.

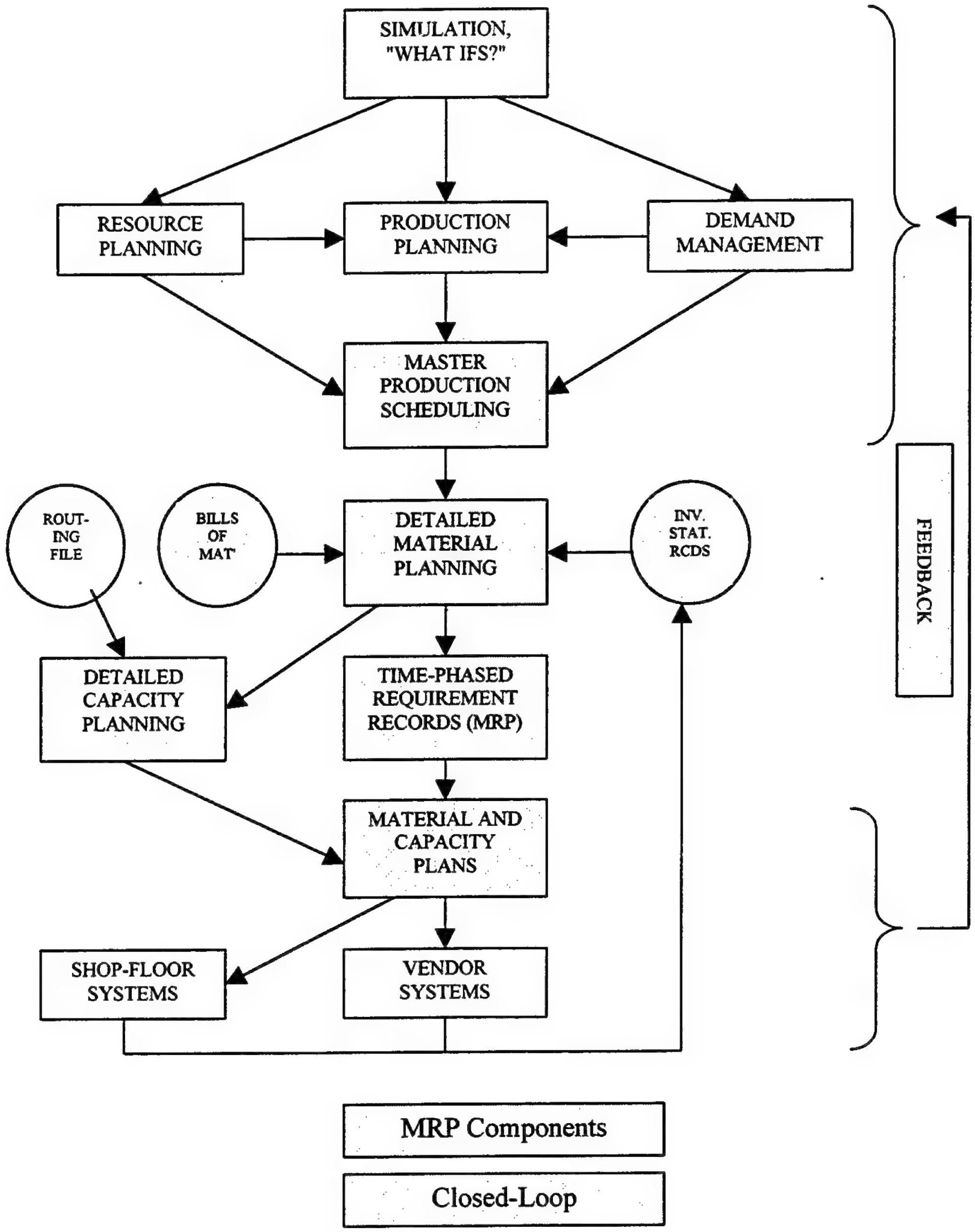


Figure 7: MRP II and its Components (Adapted from Vollmann et al., 1992: 16; Wallace, 1990: 6-8; and Chase and Aquilano, 1992: 720-721)

MRP II in Air Force Depot Maintenance

In the mid 1980s, the Air Force Logistics Command (AFLC) began exploring the possibility of adding an MRP II system to their Logistics Management Systems (LMS) modernization program. Following a 1985 study by a private consulting firm, AFLC decided to purchase a modified commercial MRP II system for use at the Air Logistics Centers (Severs, 1991: 17). In 1988, after a two-year source selection, Grumman Data Systems (GDS) was awarded a contract to develop the Depot Maintenance Management Information System (DMMIS). The stated objective of the new system was to "provide AFLC maintenance organizations with the capability to effectively determine and assure that the necessary resources are available at the centers to perform their missions successfully" (Severs, 1991: 18). At the time of DMMIS' development, organic depot maintenance was supported by over 50 individual computer systems, of which some 29 were to be replaced by DMMIS (Severs, 1991: 5). Implementation of the system began with a pilot test at Ogden Air Logistics Center (OO-ALC) in 1990.

The decision to migrate to an MRP II system at the ALCs was predicated, at least in part, on the assumption that military repair operations were similar in many ways to traditional manufacturing operations. In some regards, this assumption holds. For example, both environments use advanced requirements planning, capacity restrictions, and material availability to schedule shop floor activities. The environment in a military repair facility differs in many critical ways, however. In a traditional manufacturing setting, component requirements for end-item production are known and constant. Assuming the end-item forecasts are relatively close, exact material requirements can be calculated. By contrast, in a military repair setting exact processes and materials usually can not be determined until after evaluation and inspection has been accomplished. As a result, there is an associated high level of uncertainty that is

characteristic of such a setting (Severs, 1991: 21). Figure 4 illustrates the general process of depot repair to further clarify this point.

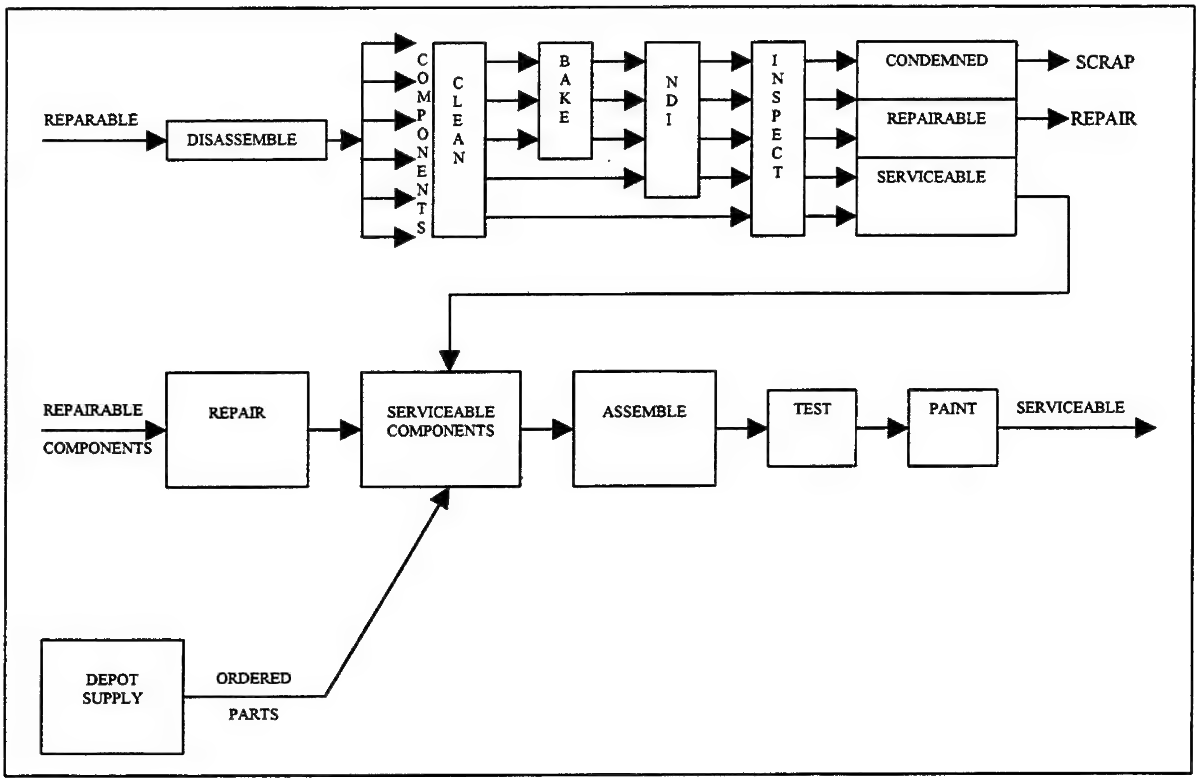


Figure 8: Typical Disassembly and Repair Flows in Depot Maintenance
(adapted from Demmy and Giambrone, 1990: 9)

As the GAO noted in 1990, the depot repair environment is extremely complex. The depot system at that time employed over 39,000 people repairing some 1,200 aircraft, 1,200 missiles, 6,400 engines, and 1.1 million other reparable items. They further point out that a single engine can contain some 1,800 parts, and can use 12 departments over 6 subassembly areas to perform its maintenance (GAO, 1990: 3). Still, the Air Force decided to go forward with the program.

Unfortunately, DMMIS never had the opportunity to fully prove itself in practice. The program quickly experienced cost overruns and delays, and was eventually cancelled. The GAO

reported in 1989 that the DMMIS contract estimate, originally $85 million in 1984, had risen to over $242 million by 1988. In addition, the Air Force expected full operational capability by February 1989, but as of the 1989 report that estimate had changed to September 1993 (GAO, 1989: 3).

The Air Force attributed the overruns and delays to poorly defined initial requirements (GAO, 1989: 15). As requirements changed, the scope of the project quickly grew out of control. Compounding the problem was a set of conflicting independent reports issued from 1985 to 1988. The first stemmed from a contractual study by Deloitte, Haskins, & Sells in 1985 that reported that a commercial MRP II software package would satisfy 90-95% of DMMIS requirements. The Air Force Audit Agency later reported that a more realistic estimate was 65-70%. The latter estimate was used to revise cost estimates, but a 1988 study by Entek, Inc. reported that the commercial MRP II software would satisfy only 51% of DMMIS requirements. The estimate was not updated at this time, however (GAO, 1990: 4). Synergy, Inc. conducted a study at about the same time and concluded that "adapting [MRP II] to the depot repair environment was risky" (GAO, 1990: 4). Their assessment was based primarily on a survey of companies in the private sector, in which they had found little success in using modified MRP II software for repair environments (GAO, 1990: 4).

Repairability Forecast Model (RFM)

Overview

The Repairability Forecast Model (RFM) is an inventory control system developed by CACI International under contract with the San Antonio Air Logistics Center (SA-ALC), Kelly Air Force Base, Texas. It has also recently been installed for use at the Propulsion Directorate of the Oklahoma City Air Logistics Center (OC-ALC/LP). The system was developed to provide users with a "forward look" at material requirements, in an attempt to avoid awaiting parts (AWP)

work stoppages and increase shop productivity in an Air Force depot environment (RFM Background Paper, YEAR: 1). It is currently under consideration to be included in the Air Force Materiel Command's (AFMC) "standard suite" of information systems to support the Agile Logistics initiative (RFM Background Paper, 1996: 1).

RFM regularly retrieves data from over a dozen Air Force and DLA computer systems and incorporates them into a single database. It then presents this data in report and query formats to provide users with the capability of assessing the feasibility of current production schedules as related to material requirements. Table 3 below identifies the various systems from which RFM pulls data, while Table 4 describes the specific data elements pulled from each system.

Table 3: System Inputs to RFM (Adapted from RFM Users Manual, 1997: 1)

SYSTEM DESIGNATOR	SYSTEM NAME
D035	Stock Control and Distribution (SC&D) System
D041	Recoverable Consumption Item Requirements System
D062	Economic Order Quantity (EOQ) Buy Computation System
PETS	Program Execution and Tracking System
PETS	D043 Master Item Identification Control System
D075	Automated Repair Requirements Compilation System (ARRCS)
G005M	Bill of Material
D200F	Application, Program, Indenture (API) File
G009	Government Furnished Material Transaction Reporting System
G004L	Job Order Production Master System
DLA	Various systems

Table 4: RFM Data Elements and Their Origins
(Adapted from RFM Users Manual, 1997: 1-2)

SOURCE SYSTEM	DATA ELEMENTS	UPDATES
D035	Assets on hand (serviceable and reparable); Interchangeability and Substitutability (I&S) Grouping; order of use; unit cost (backup source); backorder quantity	Daily (D035B)/ Monthly (D035K)
D041	16 quarters production; projected available reparable assets; applications number; applications requirement; mission item essentiality code (MIEC); lead times	Quarterly
D043	Noun; part numbers; unit cost (primary)	Monthly
D062	Lead times; mission item essentiality code	Quarterly
D143B	Equipment specialist/item manager code; source of supply (SOS); expendability, recoverability, repairability category (ERRC)	Monthly
PETS	J041-Post delivery quantities and delivery dates; J041-Pre count (quantities on purchase request)	Weekly
D075	Management of Items Subject to Repair (MISTR) requirements; unit repair cost	Quarterly
G005M	Operation codes; units per assembly; replacement percents; issues; end item production; component National Stock Numbers (NSNs); production numbers (PDNs); part numbers	Monthly
D200F (API)	NSNs; material management aggregation code (MMAC); ERRC; component NSN; component ERRC; application number; next higher assembly	As required
G009	Contractor name; contract number; production manager code; serviceable and reparable quantities on hand; component issues; end item production	Monthly
G004L	Production numbers; NSNs (end item identity); end item production for current quarter	As required
DLA	Assets available; purchase request quantity; contract delivery quantity; date delivery due in; IM code; unit cost; lead times; back order quantity; annual worldwide demand quantity	Monthly

RFM's Similarities to MRP

Conceptually, RFM is very similar to an MRP system. It provides an assessment of repair supportability using the three inputs illustrated in Figure 5, which are provided from that data elements described above (RFM Users Manual, 1997: 5). Below each RFM input in

parentheses is the associated MRP input upon which it is based. Like a closed-loop MRP system, RFM also allows the user to conduct "what if" analyses by changing input values on line, and then allowing RFM to recalculate its supportability assessment. In keeping with MRP logic, RFM assesses supportability within the total lead time, comprised of both administrative and production lead times (RFM Users Manual, 1997: 5).

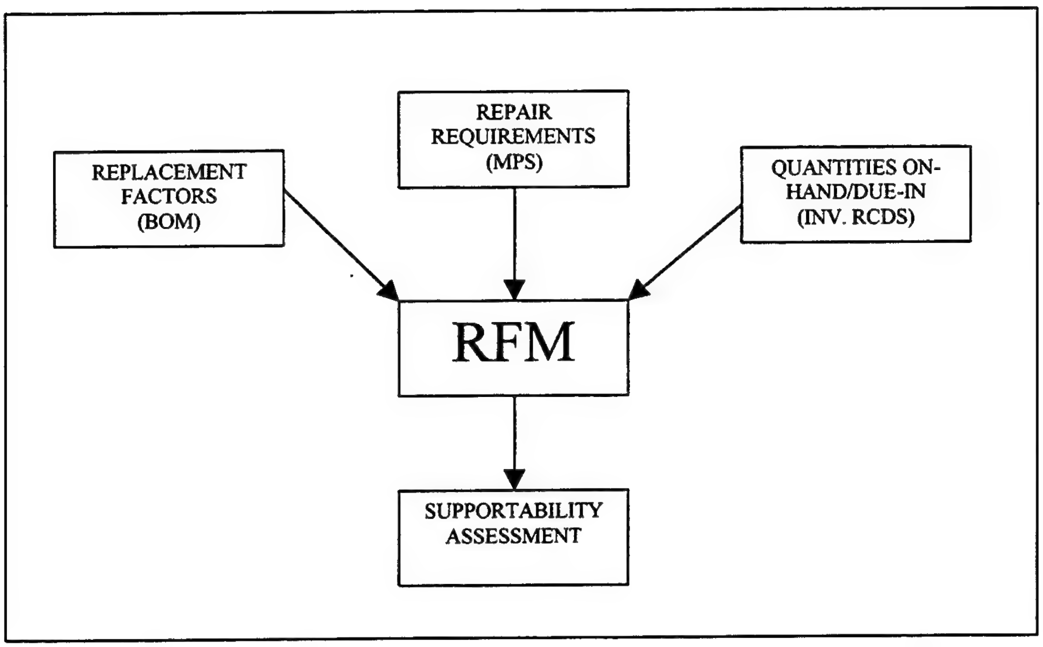


Figure 9: RFM Input/Output Model (Adapted from RFM Users Manual, 1997: 5)

Differences Between RFM and MRP

Because RFM is designed specifically for a repair environment, there are two important differences that warrant discussion. The first relates to the Bill of Materials. As previously noted, in a traditional manufacturing environment the Bill of Material (BOM) is static and known. To build a bicycle, for example, a firm knows it needs two wheels, two pedals, one handlebar assembly, one seat, etc. With such a direct relationship between independent end item demand

and the dependent demand of its associated components, it is a relatively straightforward procedure to calculate material requirements. By contrast, in a repair environment the components used in repair activities vary from job to job. It is difficult to determine exactly what will need to be fixed before the item arrives at the repair facility. In the case of the previous example, a bicycle may arrive at a repair facility with a flat tire, a broken pedal, two broken pedals, etc. Until it arrives, the material requirements are unknown.

Air Logistics Center computer systems attempt to solve this inherent problem by use of replacement percentages in its bill of materials (G005 computer system). RFM uses a similar technique with its three types of "replacement factors" (RFM Users Manual, 1997: 43). The first replacement factor used by RFM, denoted "RPLFCTR8" in the system, is calculated by dividing eight quarters worth of component issues by the associated end-item production for the same period:

$$\text{RPLFCTR8} = \frac{\text{8 quarters of component issues}}{\text{8 quarters of end-item production}} \tag{14}$$

The second replacement factor (RPLFCTR4) is calculated by dividing the four most recent quarters of component issues by the four most recent quarters of end-item production:

$$\text{RPLFCTR4} = \frac{\text{4 quarters of component issues}}{\text{4 quarters of end-item production}} \tag{15}$$

The final RFM replacement factor (RPLFCTRU) is calculated by multiplying the units per assembly (UPA) by the replacement percentage in the Bill of Materials:

$$\text{RPLFCTRU} = \quad \text{UPA X Replacement Percentage} \qquad (16)$$

Calculation of the three replacement factors in equations (14) through (16) above does not take into consideration the various work-around actions taken by shop technicians in the repair process (RFM Users Manual, 1997: 43). The specific replacement factor used in the assessment is chosen by the user, depending on the characteristics of the end-item being assessed.

The second important difference between RFM and MRP lies in the intended use and scope of the system. RFM was initially developed to "minimize design risk while taking advantage of existing database structures" (RFM Background Paper, YEAR: 2). As opposed to a complete migration to a full MRP system, RFM provides a low-cost means of accessing existing data to be used in material and production decisions. In essence, it epitomizes Eliyahu Goldratt's criticism of MRP that it is "an excellent database, but it does not provide adequate scheduling" (Chase and Aquilano, 1989: 659). The developer lists three uses for the information that RFM provides (RFM Background Paper, YEAR: 2):

1. It can be used as a trigger to expedite material deliveries
2. It can support short-term decision making, such as make-or-buy decisions
3. It can be used to develop realistic production schedules based on material availability

III. Methodology

Introduction

This chapter will discuss the experimental design and analytical methodology employed in this study. It begins with a general discussion of the issues and steps in designing an experiment, and then goes on to discuss the specifics of this study within that framework. The research problem is revisited briefly to lay the groundwork for subsequent design-related issues. Next, the determination of applicable factors and levels is discussed, followed by a related discussion of the relevant response variables. The analytical methodology is then outlined. Finally, simulation modeling is presented and discussed as the most appropriate experimental tool for a problem of this type.

Experimental Design

Many authors have broken down the experimentation process into a sequence of steps in an effort to clarify the process. Montgomery presents a seven-step procedure (Montgomery, 1991: 9-11):

1. Recognition of and statement of the problem
2. Choice of factors and levels
3. Selection of the response variable
4. Choice of experimental design
5. Performing the experiment
6. Data analysis
7. Conclusions and recommendations

These steps will be followed throughout the remainder of this report. This chapter is concerned with steps one through four above. Chapter IV will discuss steps five and six, performing the experiment and analyzing the data. Finally, Chapter V will present conclusions and recommendations.

Step 1: Recognition of and statement of the problem

The procedure used to identify the problem involved three integrated steps. The first was a site visit to the Oklahoma City Air Logistics Center LP Directorate (OC-ALC/LP), accomplished in December 1997. An LP representative gave a tour of the entire facility, and most front and back shop operations were seen and explained. In addition to the tour, several interviews and meetings were held to provide insight into the depot repair process. Continual telephone contact was maintained following the site visit and throughout the period of this study, and ALC personnel proved invaluable to the development of an accurate model.

The second problem identification step involved a comprehensive literature review of research pertaining to EOQ and MRP theory and application, as well as a review of the RFM system. The literature review augmented the site visit by providing a broad overview of the latest research in inventory management systems. Following the initial literature review, the third step involved analyzing data provided by the ALC. The data were then used to formulate a representative reparable item for inclusion in the simulation model. A more detailed discussion of this process appears later in this chapter. After completing the above three steps, the characteristics of depot operations and related inventory challenges were fully understood, making the experimental design possible.

Although already discussed briefly in Chapter I, it is important now to restate the problem driving the current research. The overarching problem facing the Oklahoma City Air Logistics Center's Propulsion Directorate (OC-ALC/LP) is one of engine availability. One of the most pervasive problems LP faces is a shortage of parts, particularly those that hold up or delay maintenance actions on engines. Production capacity is arguably less of a challenge than material shortages, since production throughput can be increased or altered using overtime or schedule changes. In this way, there is a measure of short-term control over production capacity. Material shortages, however, are often difficult to overcome. Management actions such as cannibalization,

use of substitute or interchangeable parts, and repair of component parts and subassemblies can help, but in general material shortages tend to be the most challenging in the short-term.

As discussed in Chapter II, the Department of Defense's reliance on the Wilson EOQ Model for calculating material buys has been relatively ineffective. Despite its robustness, use of the model has resulted in both shortages and excess at all echelons. Currently, the Air Logistics Centers (ALCs) are using the Depot Repair Enhancement Program (DREP) and its several derivatives to manage the production process. On a theoretical level, DREP attempts to place all functional areas related to the repair of an end item, including material control, under the control of a single person called the "fixer." The fixer holds monthly DREP meetings to identify problem areas and formulate solutions. Unfortunately, with regards to material shortages this process is generally reactive in nature. Production and supply personnel generate several ad hoc reports which isolate the "pacing items" that are currently holding up production. The list of pacing items averages approximately 200 items at any given time, and consumes a great deal of manpower in researching and problem resolution.

San Antonio Air Logistics Center (SA-ALC), in an attempt to adopt a more proactive approach to material management, contracted with CACI International to develop the Repairability Forecast Model (RFM). RFM, as discussed in Chapter II, retrieves data from over one-dozen legacy systems and consolidates them into a central database. It then uses MRP logic to generate supportability assessments, which identify potential material shortfalls within and beyond the lead time. OC-ALC has recently installed the system at their facility, and it is being explored for use as both a material control system and a parts ordering system. In the latter role, it would generate material requirements based on MRP calculations, which would then be transmitted to DLA for ordering.

The research problem being investigated in the current study is the appropriateness of MRP use as a parts ordering system in the ALC environment. It can easily be argued that RFM

will provide users with material visibility, so that problems can be addressed in advance of production delays. The step from such a usage to actual parts ordering is a large one, however, and it is important to test MRP logic under the conditions associated with an air logistics center. If MRP logic holds in an ALC environment, then it is indeed appropriate for DLA to order parts based on RFM's output. If not, great care must be exercised to use RFM within the constraints of its effective limits. The current research attempts to answer this important question.

<u>Step 2: Choice of factors and levels</u>

The factors chosen for this study are based on existing research in inventory management. The first is simply the inventory system employed. It includes two levels: EOQ and MRP. Three additional factors were chosen as among the most critical in determining the success or failure of an inventory system: demand uncertainty, demand variability, and lead time variability. For each of the three factors above, three levels have been chosen which represent the full range experienced by OC-ALC's Propulsion Directorate. The specific levels associated with each of the factors are discussed in more detail below.

Factor 1: Inventory System

Factor 1 contains two levels, which correspond to the two inventory systems under study. The first is the Wilson's EOQ model currently used by the U. S. Air Force for consumable items. Chapter II identified the major components of the EOQ model as annual demand, holding cost, and ordering cost. Annual demand, in keeping with Air Force policy, was calculated quarterly by the model as an eight-quarter moving average (AFMCI 23-105, 100). Holding and ordering costs were likewise determined from current Air Force policy (AFMCI 23-105, 194). The holding cost percentage used was 0.17 for all consumable items in the study. This factor was then multiplied by the unit cost of each item to arrive at an annual holding cost per item. The total annual holding cost is then calculated by multiplying the annual holding cost per item by the average inventory level for each item. Ordering cost was set at a constant $405 per order. AFMCI 23-

105 sets a "break point" above which the ordering cost increases to $823 per order, but the consumable items included in the simulation model all fell below this point.

The MRP model was based on the traditional MRP calculation array found in any MRP text. The array is illustrated below in Table 5, in which the lead time is assumed to be one period and the EOQ lot-sizing rule is used with an order quantity of 30. Future requirements are determined by comparing the on-hand balance from period *t-1* plus the scheduled receipts in period *t* with the gross requirements for period *t*. If the on-hand plus scheduled receipts are less than the gross requirement for a period, an order release is planned, offset by the lead time. In the simulation model employed in the present study, a 39-week planning horizon was used, and the entire MRP array was regenerated on a weekly basis. The length of the planning horizon was derived by taking the longest lead time of all parts (205 days = 29.3 weeks), and rounding it up to the nearest quarter (39 weeks), since production forecasts are generated quarterly. In the initial set of pilot runs, lot-for-lot ordering was used, in which the exact amount needed for the period one lead-time away was ordered in each period. Because of the high ordering cost relative to the holding costs for most consumable items, lot-for-lot ordering resulted in unrealistically high inventory costs. As such, the EOQ lot-sizing technique was used for the final analysis. Further discussion on the results of the different lot-sizing techniques is included in Chapter IV.

Table 5: Sample MRP Calculation Array (Tersine, 1994: XX)

PERIOD	-1	0	1	2	3
GROSS REQUIREMENT		8	10	12	10
SCHEDULED RECEIPTS		0	30	0	0
ON-HAND BALANCE	10	2	22	10	0
NET REQUIREMENT		0	0	0	0
PLAN ORDER RECEIPT					
PLAN ORDER RELEASE		30			

Factor 2: Demand Uncertainty

Demand uncertainty, for the purpose of this study, is defined as a combination of two phenomena. The first is general to any production or remanufacturing operation, and is simply the uncertainty inherent in a forecast of future requirements. It is this component of uncertainty that is varied within the present simulation study. Specifically, the forecasted quarterly end-item production for quarters 1 through 8 is shifted and updated quarterly. The update is simply a change in the forecast, and is determined by drawing a random number from a uniform distribution U(-X, X). The variable X is set at 0, 3, or 5 for levels 1, 2, and 3, respectively. For example, in a simulation run with demand uncertainty set at level 2, the end-item production forecast would be calculated by adding a random uniform number between –3 and 3 to the existing forecast. In this way, the forecast may be reduced, increased, or may remain the same. The second component of demand uncertainty is specific to a remanufacturing environment, and is due to the fact that the number of a particular item required in a repair is generally uncertain. This is the characteristic defined in Chapters I and II as "On-Condition Maintenance" (OCM). This component is included in the model for validity, but is not varied as an experimental factor.

Factor 3: Demand Variability

Demand variability is defined as the tendency of end-item production to vary from period to period. This factor is separate and distinct from demand uncertainty, in that demand can be relatively steady, but still uncertain. Likewise, demand can be highly variable, but relatively certain. Although the two are somewhat interrelated, they are modeled and analyzed as separate factors because of the different effects they have on the two systems under study. The EOQ model assumes constant demand, and so demand variability can have a significant effect on its performance. Demand uncertainty, however, only effects EOQ performance insofar as it increases the overall demand variability. In contrast, the MRP model is not concerned with

variability in demand so much as the uncertainty. In this case, the variability is only a concern insofar as it increases the overall uncertainty.

Three levels of demand variability were used in the present study, each utilizing a triangular distribution with distinct parameters. Actual end-item quarterly production data were analyzed for eight quarters and used to develop the distribution and its parameters. Level 1 represents deterministic demand at the average level experienced in the historical period. In level 2, quarterly demand was drawn from a triangular distribution with parameters 50, 66, and 75. This level represents the most likely quarterly production levels that the ALC will experience, based on historical data. Finally, level 3 included the full range of production levels experienced over the historical period, including the extreme values that were excluded from the level 2 distribution. Its parameters, again for the triangular distribution, were 40, 70, and 82.

Factor 4: Lead Time Variability

The final factor included in this study, and traditionally the most significant in the literature, is lead time variability. Unfortunately, historical data were not readily available from the ALC at the time of data collection. In lieu of actual data, three levels were selected that represent reasonable estimates. In terms of the model, the lead time variability was identified by use of a coefficient of variation (Cv). The coefficient is defined in equation 17 below (Bobko and Whybark, 1985: 420):

$$Cv = \frac{\sigma}{\mu} \tag{17}$$

Where σ = Standard Deviation
μ = Mean

The Cv factor was primarily used for its ease of modeling, but has been shown to be a robust descriptor for research purposes (Bobko and Whybark, 1985: 426). The three values of Cv corresponding to levels 1 through 3 of this factor were 0, 0.2, and 0.4, respectively. A zero Cv

represents deterministic lead times, while the remaining two represent stochastic lead times with two levels of variability. Although supporting data were not available, the levels of variability chosen were validated as reasonable by ALC personnel. The mean lead times were taken directly from the RFM system.

As an illustration of how the Cv was used in the present study, consider a part with a mean lead time of 206 days. At a Cv of zero, the lead time will always be 206 days. If the Cv is changed to 0.2, the lead time is now drawn at random from a normal distribution with a mean of 206 and a standard deviation of Cv X μ:

$$0.2 \times 206 = 41.2$$

Therefore, we can expect that the lead time will fall within the interval 206+/- (2 X 41.2) approximately 95% of the time. More directly stated, the lead time will generally fall between 123 and 288 days. If the Cv is increased to 0.4 (level 3), that range becomes 41 to 370 days. Although on the surface such a range may appear excessively large, in practice there is in fact a high degree of lead time variability associated with many consumable parts. In any event, the three levels chosen encompass the majority of the full range of possibilities experienced by the LP directorate.

<u>Step 3: Selection of the response variables</u>

Response variables are the performance measures that characterize the outcome of the experiment. It is therefore important to determine their ability to provide useful information about the process being studied (Montgomery, 1991: 10). In inventory systems, material availability and inventory-related costs are generally used as performance measures. These two categories were used in the present study. The average number of awaiting parts (AWP) days per repair was used as a measure of material availability, while the sum of annual ordering and holding costs was used as a measure of cost performance. The latter is relatively straightforward

and was discussed in the section on the EOQ model above. The material availability measure, however, warrants a brief explanation.

Material availability can be estimated using operational measures, such as aircraft availability, end item production, etc. These measures, although tying material availability to the "bottom line," tend to be indirectly linked. As a result, strong inferences regarding the role of material availability become difficult. In order to limit the research results to only that portion of the operational measure that is the direct result of material availability, traditional inventory performance measures were explored. Several such measures are frequently used, the most common being backorders and fill rate. The problem with both is that they tend to ignore the operational impact of a lack of parts. Backorders can be high, for example, but if each is filled in one day there is hardly a problem. Conversely, a single backorder can have a crippling effect if it is for a critical part and if it is outstanding for a long period. As a result, "awaiting parts (AWP) days" has been selected as the measure of material availability, representing the average number of days that a repair is awaiting parts. In many cases, this measure will represent the number of days production is held up due to material shortages. In others, it will represent a degree of "workarounds" that have a negative impact on production.

Step 4: Choice of experimental design

The choice of an experimental design is a critical element with regards to the validity of experimental results. It involves the "consideration of sample size (number of replicates), the selection of a suitable run order for the experimental trials, and the determination of whether or not blocking or other randomization restrictions are involved" (Montgomery, 1991: 10). For a study like the present one, it also involves the selection of a method for obtaining output data.

Modeling of physical systems is often relatively straightforward, but many problems arise when attempting to model large, complex systems. First, fundamental laws, like the laws of physics for example, are generally not available. Second, the procedural and policy-related

elements inherent in most business environments are often difficult to quantify and capture in a model. Third, system randomness is usually a very significant factor. Finally, there is a human factor that plays an integral role in the system's performance (Pritzker, 1995: 4). As a result of these inherent problems, simulation modeling has become a popular technique to analyze such systems. In addition to alleviating many of the problems associated with the modeling of complex systems, simulation modeling allows inferences to be drawn without building a proposed new system, or disturbing or destroying the existing system (Pritzker, 1995: 6).

Simulation modeling is generally regarded as appropriate for a wide range of applications. Simulation can be used to study and experiment with interactions within a complex system, and it allows the effects of changes to be estimated at a relatively low cost. If analytic solutions to a problem are possible, simulation can be used to reinforce and verify the results. Finally, it can be used in experimenting with new designs or policies prior to implementation, thus making it an important decision tool for managers and researchers (Banks, Carson, and Nelson, 1996: 4). In a study of 137 large firms, 84 percent indicated that they used simulation in decision making. In fact, it was second only to statistical analysis, at 93 percent usage. Similar studies have found simulation consistently ranked near the top in terms of popularity, utility, and familiarity (Law and Kelton, 1991: 2).

Like any analysis tool, simulation modeling has many advantages and some limitations. One of the most important advantages of using simulation modeling is its relatively low cost. In this respect, it allows in depth analysis of new policies, procedures, and system designs without disrupting the normal flow of operations, and without premature commitment of scarce resources and funds (Banks, Carson, and Nelson, 1996: 5). In contrast, real-world pilot tests of these prospective changes can result in loss of production and can be extremely costly and time-consuming. By its very nature, simulation allows time to be compressed, making it a very fast and efficient tool for analysis. Many different variables can be subjected to change in a

controlled environment, presenting endless analysis possibilities. Finally, virtually any "what if" question can be answered using simulation, which makes it ideal for analysis of capital investments and new system design (Banks, Carson, and Nelson, 1996: 5).

Several disadvantages have tempered the effectiveness of simulation despite its many advantages, however. The first is that model building requires specialized training and experience, and as such its effective use relies heavily on the skill of the programmer. Second, selecting the appropriate experimental methodology is critical to the resulting analysis. Again, this process requires a specialized knowledge of simulation and statistical analysis. Third, simulation modeling can be expensive and time consuming. Complex models can take a great deal of time to develop, and can subsequently tie up a great deal of computer time to run. This disadvantage has become less significant with advances in computer speed and technology, but some sophisticated models can still be cumbersome even today. Finally, simulation is sometimes used even where analytic solutions are possible. In real-world applications, however, the latter is rare (Banks, Carson, and Nelson, 1996: 5). Despite its disadvantages, simulation is the tool of choice for many applications, particularly where knowledgeable people are available to implement it.

Pritzker has organized the simulation process into a series of eleven steps (Pritzker, 1995: 10-11). Several of these steps overlap with those in Montgomery's experimental design process, but are included again here to maintain the complete philosophy they represent:

1. *Problem Formulation.* The definition of the problem to be studied including a statement of the problem-solving objective.
2. *Model Formulation and Specification.* The abstraction of the system into mathematical-logical relationships in accordance with the problem formulation.
3. *Data Acquisition.* The specification and collection of data.
4. *Model Translation.* The preparation of a model for computer processing.
5. *Verification.* The process of establishing that the computer program executes as intended.
6. *Validation.* The process of establishing that a desired accuracy of correspondence exists between the simulation model and the real system.

7. *Strategic and Tactical Planning*. The process of establishing the experimental conditions for using the model.
8. *Model Use*. The execution of the simulation model to obtain output values.
9. *Analysis of Results*. The process of analyzing the simulation outputs to draw inferences and make recommendations.
10. *Implementation*. The process of implementing decisions resulting from the simulation.
11. *Documentation*. The documenting of the model and its use.

Step 1, problem formulation, has already been discussed in some detail at the beginning of this chapter. Appendix B provides a detailed description of the simulation model used in this study, as well as its associated specifications. Necessary data was stipulated in the early stages of model development, and was coordinated with personnel from the Production and Management offices of the OC-ALC/LP Directorate. The data were provided for all parts in one of the major engine end-items repaired by OC-ALC/LP, and were intended to represent the worst case in terms of parts availability. Specifically, the following data were requested and provided:

1. Indentured list of all parts in the component
2. Demand history for the end-item and all associated parts
3. All applicable data for each part, including such things as unit cost, units per assembly (UPA), and replacement percentage

Using the data provided by OC-ALC/LP, the model was translated to computer code (step 4) using Pritzker's AWESIM™ simulation software. To simplify the model while retaining the validity of results, a product structure was developed using the general characteristics of the parts in the end-item. The resulting product structure contained 4 reparables and 4 consumables at level 1, and an additional 4 level 2 consumables indentured to reparables 1 and 2. The number of reparables and consumables in the model at each level is proportionally consistent with those of the actual end-item. Appendix A contains a complete list of the parts associated with the end-item in this study, as well as a discussion of how the resulting model parts were selected and characterized.

To ensure that the parts selected were representative of the full range of those found on the high speed compressor, the demand histories of all of its parts were first analyzed and

categorized. In the case of the reparables, the four major parts on a high speed compressor are the spacer, stator, blade, and disk. These parts are found in each of the many stages in a compressor, and account for about 84% of its reparable components. As such, these were selected as the four reparables, and the part characteristics for the model were calculated by aggregating the data for each part type. For example, the model part representing the stator is defined by the aggregated characteristics of the prime and substitute 10^{th}, 11^{th}, 12^{th}, 13^{th}, 14^{th}, and 15^{th} stage stators, a total of 20 national stock numbered items (NSNs).

In the case of the consumable parts, the relationship is less straightforward. The number and diversity of consumable parts made such a direct selection impossible, and so the consumable parts were categorized according to their demand histories. The categories are summarized in Table 6 below. The resulting five categories were then used to develop the characteristics of the eight consumables included in the model. For each category, data were aggregated for all parts in that category, with the resulting overall characteristics applied to the corresponding model parts. It should be noted that the categories below account for about 95% of the consumables analyzed, with the remaining 5% not included. The frequencies were used to ensure that the proportional shares of different types of consumables were maintained in the model.

Table 6: Categories of Consumable Parts in TF-33 High Speed Compressor

CATEGORY	NUMBER OF ISSUES IN ANALYSIS PERIOD	MEAN QUANTITY PER ISSUE	FREQUENCY	# OF PARTS IN MODEL
1	1-21	< 10	44%	4
2	1-21	10-86	14%	1
3	1-21	256-510	12%	1
4	22-41	< 86	12%	1
5	22-41	256-510	12%	1

A number of assumptions were also necessary to make the model feasible. First, end-item demand was assumed to be steady during the current quarter. This is the equivalent of freezing the master production schedule for the current period, and is valid in the sense that total

end-item production changes very little within a current quarter. In reality, the production rate within a quarter would be more variable, but the total production at the end of a quarter is generally equivalent to the plan going into that quarter. In the context of the simulation model, this assumption was necessary since a variable production rate would cause end-item production within a quarter to deviate, sometimes significantly, from the planned production going into that quarter.

The second assumption inherent in the simulation model is that planned safety stock is not allowed. This assumption was made to preclude any bias toward one system or the other. The systems each have associated techniques for determining safety stock levels, and so inclusion of a safety stock level would have confounded the results of the experiment unnecessarily.

The third assumption is that backorders are not allowed. This assumption was made primarily for the sake of simplicity, since backorders would have complicated the model. Once again, the focus on parts availability as measured by AWP days was maintained in the model, and backordering of parts, given the long lead times experienced on most parts, would not have had a significant impact on parts availability.

The next assumption relates to parts usage. In overhaul repairs, it was assumed that all reparable parts were repaired, and that all level 1 consumable parts were replaced. In practice this is not always the case, but the assumption was made for simplicity. In OCM repairs, two level 1 parts were selected for repair or replacement, and each part had equal probability of being selected. Again, this is not necessarily the case in practice, but absent historical replacement data an assumption was necessary. Despite the parts usage assumptions, it was hoped that the overall variability in parts demand was captured over time by testing the model at extreme levels of uncertainty and variability.

Repair times were assumed to be deterministic, and repair labor was assumed to be unconstrained. In practice, repair times vary and certain bottleneck backshops experience finite

capacity. However, in order to focus on the effects of material availability, these assumptions were deemed necessary, albeit somewhat invalid.

For the EOQ system model, orders were assumed to be placed on a weekly basis. In practice, orders are placed daily, but in order to eliminate any bias in the statistical comparisons between the two systems, the orders need to follow the same schedule. Since the MRP model regenerated and ordered on a weekly basis, the EOQ model was set as the same.

It was next assumed that EOQ lot-sizing was employed by the MRP system. In pilot runs of the model, the MRP system used lot-for-lot ordering, and it was observed that both cost and availability performance was extremely poor. This can be attributed to the fact that the ordering cost is very high relative to the holding cost of most consumable items. As a result, placing frequent orders biased the results in favor of the EOQ model. Again, statistical comparisons of performance measures are only meaningful if potential biases are first removed wherever possible.

Finally, and perhaps most importantly in terms of the validity of the experimental results, the simplified product structure and characteristics used in the model were assumed to approximate those experienced in the real end-item. Testing of the model at higher levels of complexity is left for future research, and is discussed at the end of Chapter V, but for the purpose of the present study it was included as an assumption that the complexity would not unduly skew the results of the analysis.

Verification and Validation

Because of their importance to the results of a simulation study, verification and validation of the model are now discussed together under a common heading. The verification process ensures that the computer model is performing as it was intended by the modeler (Pritzker, 1995: 12). It involves matching randomly selected inputs and outputs to ensure that the actual outputs do not differ in any significant way with the theoretical expectations. Any

discrepancies noted in this step would precipitate the need for modifications to parts of the model or to the model as a whole (Pritzker, 1995: 12-13). Validation, in contrast, is the process of ensuring that the model accurately represents the real system under study. In this way, a "useful or reasonable representation" of the specific areas of interest can be attained (Pritzker, 1995: 13).

The model was partly verified using the AWESIM™ Interactive Execution Environment (IEE) feature, which allows the user to interactively observe changes in the state of the model at specified breakpoints (Pritzker, 1995: 13). In addition, code was included throughout the model to save trace values of model variables at specified points in the simulation, which were then reviewed to verify the results. This process proved to be the most time-consuming of the entire model development. Each individual sub-process in the model was first independently tested to ensure accuracy of calculations. When this was completed, the system was tested as a whole, with multiple data files used to store intermediate trace output. In most cases, as in the case of file maintenance of the data array, trace outputs were compared with hand calculations to identify discrepancies. Wherever discrepancies were discovered, the model was examined and modified to correct the discrepancies. For example, exceptionally long wait times for consumable parts prompted an investigation of the EOQ calculation process. Trace outputs indicated that the EOQ was not being updated for several items, which led to the discovery of a flaw in the process flow of the model. Dozens of such examples could be cited, but most led to minor model adjustments and are therefore omitted from this discussion.

The validation process for new systems can be difficult, since the system being studied does not yet exist. In the case of this study, RFM already exists, making the validation relatively straightforward. Since RFM uses MRP logic, the most important validation was that of ensuring that a simple MRP model would accurately represent RFM. To accomplish this validation, RFM outputs were compared with traditional MRP calculations to validate the connection. In this way,

the MRP model used in the study can be assumed to approximate the performance of both RFM and any generic MRP system.

Beyond the use of the MRP model to represent RFM, it is also necessary to validate the model with respect to its approximation of the depot production and supply operations. In this case, the validation is much more difficult because of the size and complexity of the system. Interviews with depot personnel at various times throughout the model development process proved invaluable in this effort, not only to ensure an accurate representation, but also to screen out extraneous system elements to simplify the model.

Strategic and Tactical Planning

The simulation model described above and in Appendix B was used to generate output data to estimate the performance levels of the two systems under study. The experimental design employed was a completely randomized, full factorial design with a total of 54 treatment combinations (3X3X3X2). Factorial designs are generally regarded as the most efficient for studies including two or more factors, and allow a detailed analysis of the complex relationships between the factors under study. The result is that conclusions are highly generalizable (Montgomery, 1991: 201). The overall design is illustrated in Figure 6 below.

DEMAND	DEMAND		EOQ			MRP		SYSTEM
UNCERTAINTY	VARIABILITY	Cv=0	Cv=0.2	Cv=0.4	Cv=0	Cv=0.2	Cv=0.4	LT_VAR
CHANGE	CONSTANT 62.5							
FACTOR =	TRIANG(50,66,75)							
0	TRIANG(40,70,82)							
CHANGE	CONSTANT 62.5							
FACTOR =	TRIANG(50,66,75)							
3	TRIANG(40,70,82)							
CHANGE	CONSTANT 62.5							
FACTOR =	TRIANG(50,66,75)							
5	TRIANG(40,70,82)							

Figure 10: Format, Factors, and Levels for Full Factorial Design

Ten replications were run for each of the 54 treatment combinations illustrated in Figure 10 above. The results were then used to conduct an Analysis of Variance (ANOVA) to examine the main and interaction effects present. Once the ANOVA results were analyzed, relevant multiple comparison tests were conducted to gain more insight into relationships of interest. Specifically, Tukey's Test and Bonferroni's procedure were used for multiple comparisons. Both are widely used and accepted, and are available in many statistical analysis software packages (Montgomery, 1991: 79; McClave and Benson, 1994: 867). Chapter IV contains a more detailed discussion of the experimental design and its results.

Model Use

The simulation model, once verified and validated, was used to generate output for each of the treatment combinations in Figure 10. A unique random number stream was used for each treatment, so that the experiment can be considered completely randomized and traditional ANOVA was possible (McClave and Benson, 1994: 870). Several rounds of pilot runs were used to conduct a final verification of the model, to estimate the initialization period, and to determine the minimum number of replications necessary for significant statistical results to be obtained.

One result of the pilot runs that will be discussed in further detail in Chapter V was a change in lot-sizing rule from lot-for-lot (LFL) to EOQ. Preliminary results indicated that LFL performed poorly with regard to both cost and parts availability, and as such the EOQ lot-sizing rule was used for the final analysis.

Appendix C provides a detailed look at how the initialization period was estimated. Initialization is a concern in a simulation study because for many systems the starting conditions can have a profound effect on model performance. As such, it is necessary to begin collecting statistics only after the system has reached steady state (Law and Kelton, 1991: 530). A number of techniques are available to determine the initialization period, but probably the simplest and most straightforward is the graphical procedure developed by Welch (Law and Kelton, 1991:

545). Welch offered the following sequence of steps, which were followed in the present study and are detailed in Appendix C (Law and Kelton, 1991: 546):

1. Make n replications of the simulation ($n \geq 5$), each of length m (where m is large). Let Yji be the ith observation from the jth replication (j = 1, 2, …, n; I = 1, 2, …, m).
2. Let $\overline{Yi} = \frac{\sum_{j=1}^{n} Yji}{n}$ for I = 1, 2, …, m.
3. To smooth out the high-frequency oscillations in the averages above, but leaving the trend intact, use a moving average.
4. Plot the moving average for I = 1, 2,…, m and choose the initialization period as that period beyond which it appears to have converged.

Analysis of results (step 9) is included as Chapter IV, implementation (step 10) as Chapter V, and documentation (step 11) as Appendix B, and so are omitted from the present discussion.

IV. Results

Introduction

The simulation experiment described in Chapter III was designed expressly to answer the research questions of this study. Likewise, the set of statistical tests employed was selected toward that end. To review, four research questions were identified in Chapter I:

1. Does the EOQ model adequately meet the needs of the Air Logistics Centers in ensuring consumable parts availability?

2. Would the use of Material Requirements Planning improve inventory availability?

3. Can RFM be assumed to perform at the same level as MRP, given their similarities and differences?

4. What procedural measures are necessary to ensure RFM's success?

This chapter will primarily deal with research question 2 above. Question 1 has already been addressed at length in Chapter II, while questions 3 and 4 will be discussed in Chapter V.

In order to answer the question of whether or not MRP will improve material availability over the EOQ model, it is necessary to conduct an experiment that tests both under a wide range of experimental conditions. As discussed in Chapter III, simulation modeling is ideal for an experiment of this type. For each system, a total of 27 experimental treatment combinations were tested, with ten replications per treatment. The experiment was initially run using five replications per treatment, and the resulting sample variance was then used to determine the number of additional replications needed to show statistically significant results. The results are presented below in two sections, corresponding to the two performance measures used. The first presents the results of all statistical tests using the number of AWP days as the dependent variable, while the second uses annual inventory cost as the dependent variable. The results of each individual replication are presented in table format in Appendix C, and so only mean values are presented in this chapter for clarity.

Awaiting Parts (AWP) Days as Dependent Variable

ANOVA

Table 7 below shows the template used for the completely randomized full factorial design, as well as the mean values for each treatment cell. Again, the mean values in each cell are based on the results of 10 replications.

Table 7: Mean Treatment Responses Using AWP Days as Dependent Variable

DEMAND	DEMAND		EOQ			MRP		SYSTEM
UNCERTAINTY	VARIABILITY	*Cv=0*	*Cv=0.2*	*Cv=0.4*	*Cv=0*	*Cv=0.2*	*Cv=0.4*	LT_VAR
CHANGE	*CONSTANT 62.5*	3.808	11.239	35.301	0.002	0.310	3.185	
FACTOR =	*TRIANG(50,66,75)*	4.011	12.417	21.828	0.006	0.726	3.278	
0	*TRIANG(40,70,82)*	4.024	12.670	26.225	0.031	0.347	3.676	
CHANGE	*CONSTANT 62.5*	3.974	14.617	28.880	0.016	0.511	4.975	
FACTOR =	*TRIANG(50,66,75)*	5.111	13.684	31.574	0.018	0.285	4.395	
3	*TRIANG(40,70,82)*	5.263	12.277	28.351	0.034	0.559	2.487	
CHANGE	*CONSTANT 62.5*	6.086	13.338	32.643	0.012	0.705	2.164	
FACTOR =	*TRIANG(50,66,75)*	5.203	14.620	32.580	0.017	0.429	2.746	
5	*TRIANG(40,70,82)*	5.714	14.945	27.668	0.027	0.734	6.019	

The complete set of treatment responses in Appendix C was next imported into Statistix® Analytical Software for analysis. The first statistical test conducted was a four-way Analysis of Variance (ANOVA). The results are presented in Table 8 below. Three of the four main effects show statistical significance in the ANOVA at α=0.05: system, demand uncertainty, and lead time variability. Demand variability alone did not show significance. In addition to the main effects, several first-order interactions were present that warrant further examination: demand uncertainty with system, demand variability with lead time variability, and lead time variability with system. Higher level interactions were not examined, since their interpretation is difficult and they therefore offer little to the analysis (Law and Kelton, 1991: 662).

Table 8: Analysis of Variance Using AWP Days as Dependent Variable (SPSS)

Tests of Between-Subjects Effects

Dependent Variable: AWP_DAYS

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Noncent. Parameter	Observed Power[a]
Corrected Model	58771.6[b]	53	1108.898	90.064	.000	4773.375	1.000
Intercept	40169.1	1	40169.1	3262.502	.000	3262.502	1.000
D_UNC	144.036	2	72.018	5.849	.003	11.698	.872
D_VAR	36.372	2	18.186	1.477	.229	2.954	.315
LT_VAR	18800.9	2	9400.433	763.495	.000	1526.989	1.000
SYS	28217.6	1	28217.6	2291.807	.000	2291.807	1.000
D_UNC * D_VAR	109.025	4	27.256	2.214	.066	8.855	.650
D_UNC * LT_VAR	13.727	4	3.432	.279	.892	1.115	.112
D_UNC * SYS	111.011	2	55.505	4.508	.011	9.016	.769
D_VAR * LT_VAR	122.819	4	30.705	2.494	.042	9.975	.710
D_VAR * SYS	61.527	2	30.763	2.499	.083	4.997	.501
LT_VAR * SYS	10118.0	2	5058.981	410.886	.000	821.772	1.000
D_UNC * D_VAR * LT_VAR	299.830	8	37.479	3.044	.002	24.352	.961
D_UNC * D_VAR * SYS	151.630	4	37.908	3.079	.016	12.315	.810
D_UNC * LT_VAR * SYS	7.890	4	1.973	.160	.958	.641	.084
D_VAR * LT_VAR * SYS	175.046	4	43.761	3.554	.007	14.217	.868
D_UNC * D_VAR * LT_VAR * SYS	402.249	8	50.281	4.084	.000	32.670	.993
Error	5983.814	486	12.312				
Total	104925	540					
Corrected Total	64755.4	539					

a. Computed using alpha = .05

b. R Squared = .908 (Adjusted R Squared = .898)

The results of the ANOVA are now presented graphically in Figures 11 through 14 to illustrate the magnitude of each main effect on the number of AWP days.

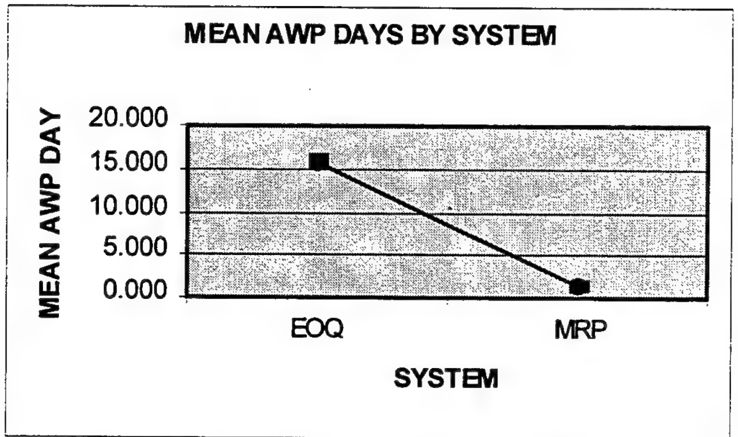


Figure 11: Main Effect of System on AWP Days

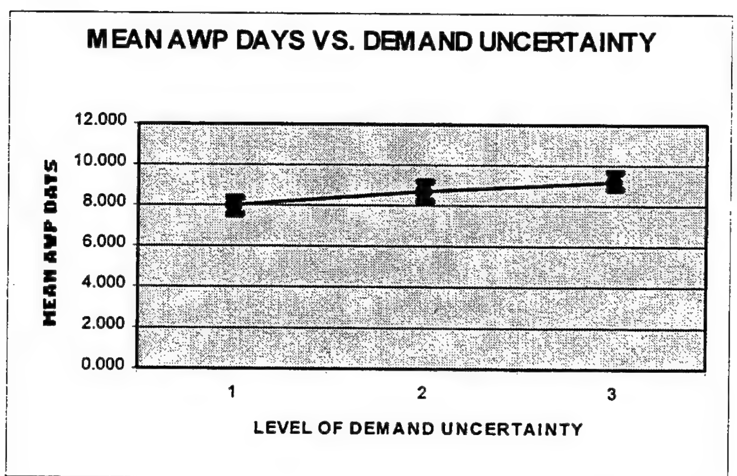


Figure 12: Main Effect of Demand Uncertainty on AWP Days

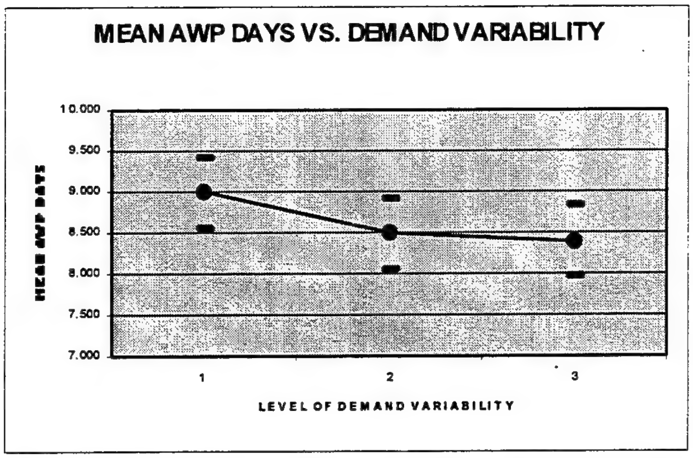


Figure 13: Main Effect of Demand Variability on AWP Days

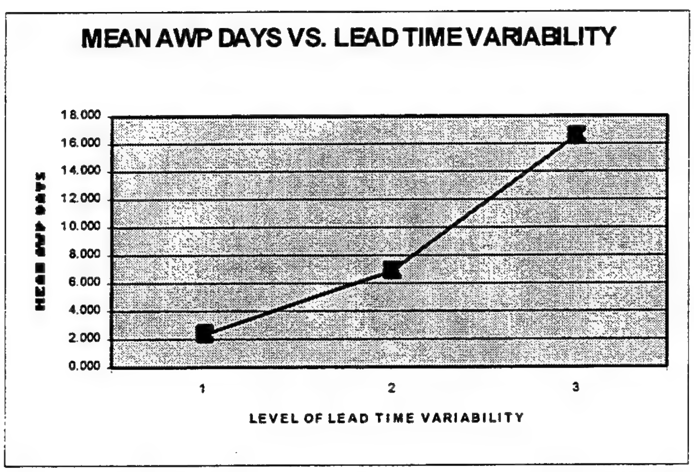


Figure 14: Main Effect of Lead Time Variability on AWP Days

Tukey's Tests for Multiple Comparisons

Having gained some insight into the significant factors and interactions present, Tukey's test for multiple comparisons was used to examine these significant factors more closely. From the graphs in Figures 11 through 14, it is evident that the system and lead time variability play a significant role in the number of AWP days experienced, but the effects of demand uncertainty and demand variability are less clear. The first set of Tukey's tests was conducted to test each of the main effects identified above.

Main Effects

Table 9: Tukey's Test for Main Effect of System on AWP Days

```
TUKEY (HSD) COMPARISON OF MEANS OF AWP_DAYS BY SYS

                           HOMOGENEOUS
   SYS          MEAN       GROUPS
---------    ----------    -----------
     1         15.854       I
     2         1.3961       .. I

ALL 2 MEANS ARE SIGNIFICANTLY DIFFERENT FROM ONE ANOTHER.

CRITICAL Q VALUE                 0.772     REJECTION LEVEL 0.050
CRITICAL VALUE FOR COMPARISON    0.5919
STANDARD ERROR FOR COMPARISON    0.3020

ERROR TERM USED: RESIDUAL, 486 DF
```

The results in Table 9 indicate that the mean AWP days experienced by the two systems are significantly different at the α=0.05 level. In addition to statistical significance, the means are very practically significant as well. They indicate that, on average, the number of AWP days experienced using EOQ is over eleven times that of the MRP system. Results of the remaining three Tukey's tests on main effects are presented in Tables 10 through 12 below. The results are consistent with the ANOVA results presented above, in that demand uncertainty and lead time variability showed statistical significance, while demand variability did not. In the case of lead time variability, the means at all three levels were statistically and practically significant. For the

demand uncertainty main effect, the difference between levels 1 and 3 was the only one that showed statistical significance, and even then it amounted to only about 1.25 days on average.

Table 10: Tukey's Test for Main Effect of Demand Uncertainty on AWP Days

```
TUKEY (HSD) COMPARISON OF MEANS OF AWP_DAYS BY D_UNC

                            HOMOGENEOUS
  D_UNC          MEAN       GROUPS
---------     ----------    -----------
    3          9.2027        I
    2          8.7228        I I
    1          7.9490       .. I

THERE ARE 2 GROUPS IN WHICH THE MEANS ARE
NOT SIGNIFICANTLY DIFFERENT FROM ONE ANOTHER.

CRITICAL Q VALUE                      3.314   REJECTION LEVEL    0.050
CRITICAL VALUE FOR COMPARISON        0.8668
STANDARD ERROR FOR COMPARISON        0.3699

ERROR TERM USED: RESIDUAL, 486 DF
```

Table 11: Tukey's Test for Main Effect of Demand Variability on AWP Days

```
TUKEY (HSD) COMPARISON OF MEANS OF AWP_DAYS BY D_VAR

                            HOMOGENEOUS
  D_VAR          MEAN       GROUPS
---------     ----------    -----------
    1          8.9869        I
    2          8.4959        I
    3          8.3916        I

THERE ARE NO SIGNIFICANT PAIRWISE DIFFERENCES AMONG THE MEANS.

CRITICAL Q VALUE                      3.314    REJECTION LEVEL    0.050
CRITICAL VALUE FOR COMPARISON        0.8668
STANDARD ERROR FOR COMPARISON        0.3699

ERROR TERM USED: RESIDUAL, 486 DF
```

Table 12: Tukey's Test for Main Effect of Lead Time Variability on AWP Days

```
TUKEY (HSD) COMPARISON OF MEANS OF AWP_DAYS BY LT_VAR

                              HOMOGENEOUS
  LT_VAR        MEAN          GROUPS
---------    ----------    -----------
     3         16.554       I
     2         6.9116       .. I
     1         2.4087       .... I

ALL 3 MEANS ARE SIGNIFICANTLY DIFFERENT FROM ONE ANOTHER.

CRITICAL Q VALUE                    3.314    REJECTION LEVEL    0.050
CRITICAL VALUE FOR COMPARISON      0.8668
STANDARD ERROR FOR COMPARISON      0.3699

ERROR TERM USED: RESIDUAL, 486 DF
```

Interaction Effects

Three of the six first-order interaction effects were shown in the ANOVA to be statistically significant at the α=0.05 level:

(1) Demand Uncertainty and System

(2) Lead Time Variability and System

(3) Demand Variability and Lead Time Variability

The first two interaction effects above, since they provide insight into the differences between the two systems, were selected for further examination. These two are shown graphically in Figures 15 and 16 below. From the graphs, it appears that the effects of demand uncertainty and lead time variability on AWP days are different for the two systems under study. In order to show statistical differences, however, Tukey's test was again used to test the effects of these two factors holding the system constant. By comparing the results of Tukey's test for demand uncertainty in EOQ with those in MRP, some insight can be gained into the nature of their relationship. The same can then be done for lead time variability.

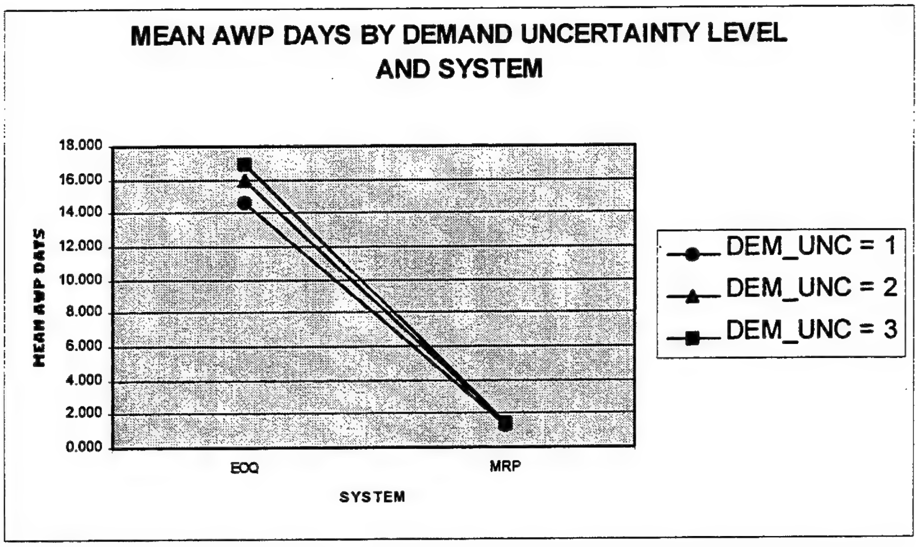


Figure 15: Interaction Effects Between Demand Uncertainty and System

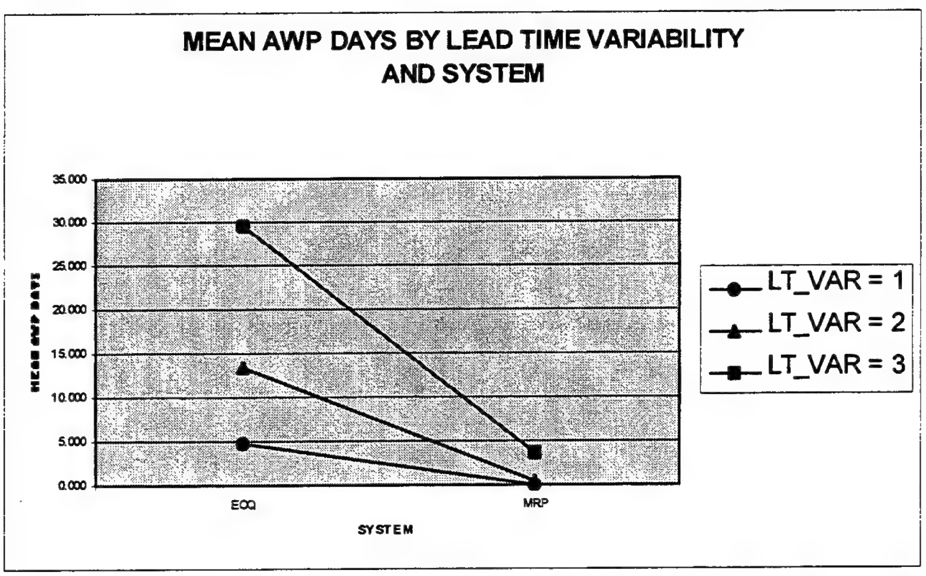


Figure 16: Interaction Effects Between Lead Time Variability and System

The results of Tukey's tests for the main effects of demand uncertainty within each system are shown in Tables 13 and 14 below.

Table 13: Tukey's Test for Main Effect of Demand Uncertainty on AWP Days: EOQ

```
TUKEY (HSD) COMPARISON OF MEANS OF AWP_DAYS BY D_UNC

                              HOMOGENEOUS
  D_UNC          MEAN         GROUPS
---------     ----------     -----------
    3           16.977        I
    2           15.970        I I
    1           14.613        .. I

THERE ARE 2 GROUPS IN WHICH THE MEANS ARE
NOT SIGNIFICANTLY DIFFERENT FROM ONE ANOTHER.

CRITICAL Q VALUE                      3.314    REJECTION LEVEL    0.050
CRITICAL VALUE FOR COMPARISON        1.6727
STANDARD ERROR FOR COMPARISON        0.7137

ERROR TERM USED: RESIDUAL, 243 DF
```

Table 14: Tukey's Test for Main Effect of Demand Uncertainty on AWP Days: MRP

```
TUKEY (HSD) COMPARISON OF MEANS OF AWP_DAYS BY D_UNC

                              HOMOGENEOUS
  D_UNC          MEAN         GROUPS
---------     ----------     -----------
    2           1.4756        I
    3           1.4280        I
    1           1.2846        I

THERE ARE NO SIGNIFICANT PAIRWISE DIFFERENCES AMONG THE MEANS.

CRITICAL Q VALUE                      3.314    REJECTION LEVEL    0.050
CRITICAL VALUE FOR COMPARISON        0.4556
STANDARD ERROR FOR COMPARISON        0.1944

ERROR TERM USED: RESIDUAL, 243 DF
```

In the EOQ model, the effect of demand uncertainty is shown in Table 13 to be statistically significant between levels 1 and 3, indicating a moderate effect. In Table 14, however, we see that demand uncertainty has no statistically significant effect on AWP days for the MRP system. The nature of the interaction between demand uncertainty and system is therefore made clearer through the comparison test results. Figures 17 and 18 further clarify this interaction.

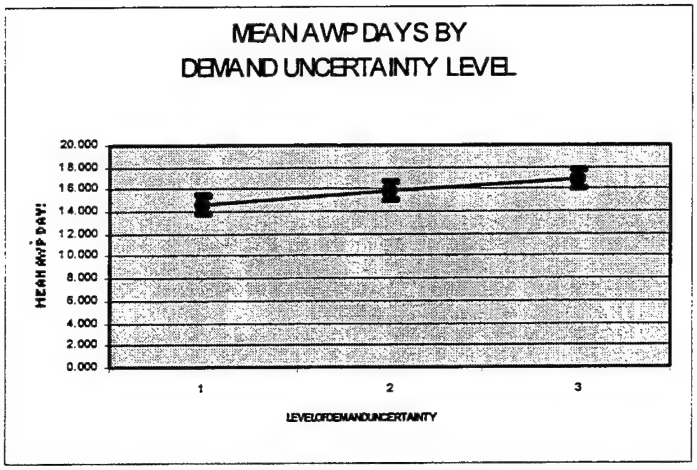


Figure 17: Main Effect of Demand Uncertainty Level on AWP Days: EOQ

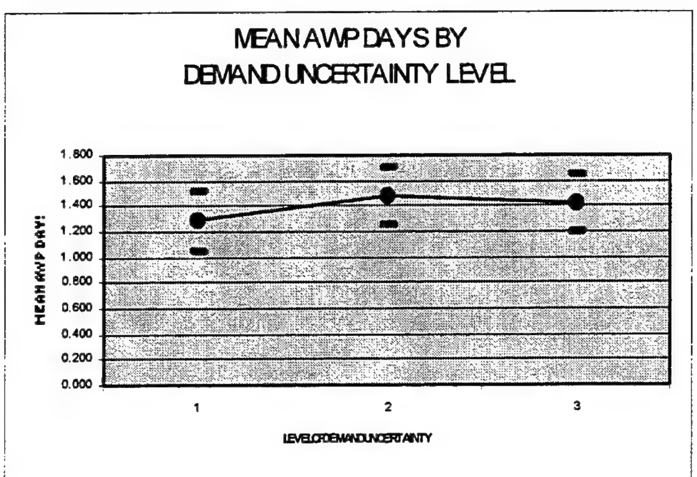


Figure 18: Main Effect of Demand Uncertainty Level on AWP Days: MRP

Taking the same approach for the interaction between lead time variability and system yields the following results in Tables 15 and 16.

Table 15: Tukey's Test for Main Effect of Lead Time Variability on AWP Days: EOQ

```
TUKEY (HSD) COMPARISON OF MEANS OF AWP_DAYS BY LT_VAR

                          HOMOGENEOUS
  LT_VAR       MEAN       GROUPS
---------   ----------   -----------
     3        29.450      I
     2        13.312     .. I
     1        4.7992     .... I

ALL 3 MEANS ARE SIGNIFICANTLY DIFFERENT FROM ONE ANOTHER.

CRITICAL Q VALUE                     3.314    REJECTION LEVEL    0.050
CRITICAL VALUE FOR COMPARISON       1.6727
STANDARD ERROR FOR COMPARISON       0.7137

ERROR TERM USED: RESIDUAL, 243 DF
```

Table 16: Tukey's Test for Main Effect of Lead Time Variability on AWP Days: MRP

```
TUKEY (HSD) COMPARISON OF MEANS OF AWP_DAYS BY LT_VAR

                          HOMOGENEOUS
  LT_VAR       MEAN       GROUPS
---------   ----------   -----------
     3        3.6583      I
     2        0.5117     .. I
     1        0.0182     .... I

ALL 3 MEANS ARE SIGNIFICANTLY DIFFERENT FROM ONE ANOTHER.

CRITICAL Q VALUE                     3.314    REJECTION LEVEL    0.050
CRITICAL VALUE FOR COMPARISON       0.4556
STANDARD ERROR FOR COMPARISON       0.1944

ERROR TERM USED: RESIDUAL, 243 DF
```

In this case, the interaction effects between lead time variability and system are less clear. Tukey's test for the main effect of lead time variability on AWP days for each of the two systems indicates that all three means are statistically different in both cases. While lead time variability appears to have a more linear relationship with AWP days in the EOQ model, its effect in the MRP model appears to be minimal at levels 1 and 2, becoming practically significant only at level 3. So although the statistical tests offer little insight into the nature of the relationship in this case, inferences can be drawn by a simple inspection of the graphs in Figures 19 and 20, and by an evaluation of the practical significance of the differences.

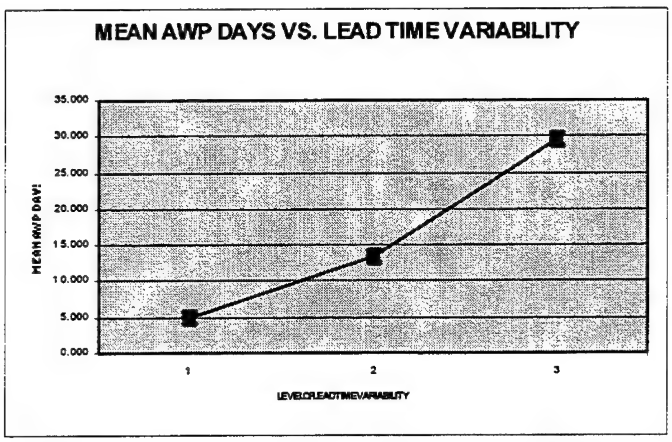


Figure 19: Main Effect of Lead Time Variability on AWP Days: EOQ

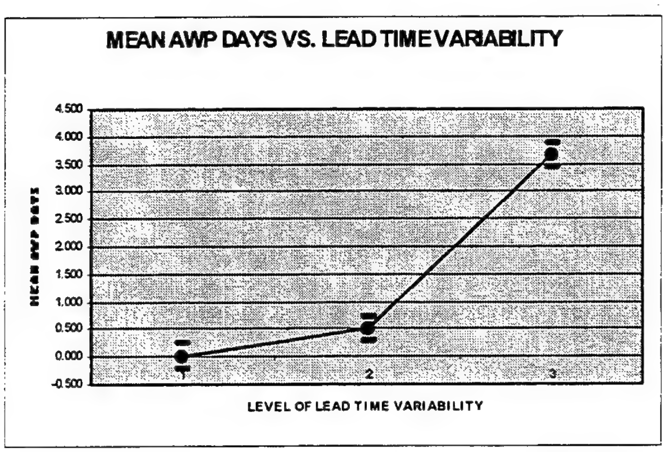


Figure 20: Main Effect of Lead Time Variability on AWP Days: MRP

Summary of Results Using AWP Days as the Dependent Variable

The preceding discussion on the main and interaction effects present in the experimental results illustrates several important points. First, demand variability and lead time variability have significant effects on the number of AWP days experienced over time. This finding is consistent with previous research, and therefore serves as further validation of the model. The second important point stemming from the experimental results relates to the different effects of demand uncertainty and lead time variability associated with each system. Demand uncertainty had a moderate effect on AWP days for the EOQ model, while there was no significant effect shown in the MRP model. Lead time variability, in contrast, showed statistically significant differences between the means at all levels for both systems. In the EOQ model, the effect of lead time variability is relatively constant and linear across the range of levels tested. For the MRP model, however, the effect of lead time variability does not become practically significant until the level is increased from 2 to 3. This indicates that MRP performance is steady within a low range of lead time variability, but that it reaches a "break point" beyond which its performance deteriorates quickly. Validation of this observation is left for future researchers, but given the literature it appears consistent with expectations.

The final point from the preceding experimental results relates directly to the research question identified at the start of this chapter. The overall main effect of the system on AWP days is statistically and practically significant. By practical significance, it is meant that the difference between the mean AWP days of 1.4 in the MRP model and of 15.9 in the EOQ model has real-world implications. In essence, it represents a two-week difference in throughput time for this simplified end-item. In terms of the research objectives of the present study, then, the effect of the system is the most relevant result observed. With the results of this section summarized, the following section presents a mirror analysis using annual inventory cost as the dependent variable. Further discussion of all results can be found in Chapter V.

Annual Inventory Cost as Dependent Variable

ANOVA

The mean values for total annual cost for each treatment combination in the experimental design are shown below in Table 17. Again, the complete set of treatment responses are found in Appendix C of this report. Table 18 shows the complete ANOVA for the design. Once again, three of the four factors showed significant main effects at the $\alpha=0.05$ level. In this case, however, the three significant factors were system, lead time variability, and demand variability. Demand uncertainty was found to be statistically insignificant. Only one first-order interaction showed statistical significance: that of the interaction between lead time variability and system. This interaction will be discussed later in this section.

Table 17: Mean Treatment Responses Using Annual Inventory Cost as Dependent Variable

DEMAND	DEMAND	EOQ			MRP			SYSTEM
UNCERTAINTY	VARIABILITY	1	2	3	1	2	3	LT_VAR
1	1	8066	8133	8212	12201	11797	11856	
	2	8079	8155	8149	12375	11736	11771	
	3	8014	8222	8488	12257	11879	11876	
2	1	8057	8105	8381	12274	11677	11658	
	2	8029	8079	8355	12392	11900	11665	
	3	8015	8123	8276	12234	11899	11895	
3	1	7969	8124	8267	12295	11714	11692	
	2	8069	8103	8244	12410	11921	11938	
	3	8110	8063	8521	12345	11849	11906	

The results of the ANOVA on annual inventory cost are consistent with expectations, since the EOQ lot-sizing rule was used in both cases. By its very nature, the EOQ model is considered robust and therefore total cost is relatively insensitive to individual violations of its assumptions.

Table 18: Analysis of Variance Using Annual Inventory Cost as Dependent Variable (SPSS Output)

Tests of Between-Subjects Effects

Dependent Variable: ANN_COST

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Noncent. Parameter	Observed Power[a]
Corrected Model	2.0E+09[b]	53	3.7E+07	510.795	.000	27072.110	1.000
Intercept	5.5E+10	1	5.5E+10	746210	.000	746210.37	1.000
D_UNC	76836.1	2	38418.0	.523	.593	1.047	.136
D_VAR	626131	2	313065	4.266	.015	8.531	.744
LT_VAR	3838077	2	1919039	26.147	.000	52.294	1.000
SYS	2.0E+09	1	2.0E+09	26770.9	.000	26770.946	1.000
D_UNC * D_VAR	226493	4	56623.3	.772	.544	3.086	.248
D_UNC * LT_VAR	88360.4	4	22090.1	.301	.877	1.204	.117
D_UNC * SYS	58959.8	2	29479.9	.402	.669	.803	.115
D_VAR * LT_VAR	641892	4	160473	2.186	.069	8.746	.644
D_VAR * SYS	276505	2	138252	1.884	.153	3.767	.392
LT_VAR * SYS	1.5E+07	2	7303548	99.512	.000	199.024	1.000
D_UNC * D_VAR * LT_VAR	334471	8	41808.9	.570	.803	4.557	.266
D_UNC * D_VAR * SYS	299719	4	74929.8	1.021	.396	4.084	.323
D_UNC * LT_VAR * SYS	243966	4	60991.4	.831	.506	3.324	.266
D_VAR * LT_VAR * SYS	79838.5	4	19959.6	.272	.896	1.088	.110
D_UNC * D_VAR * LT_VAR * SYS	705145	8	88143.1	1.201	.296	9.608	.559
Error	3.6E+07	486	73393.6				
Total	5.7E+10	540					
Corrected Total	2.0E+09	539					

a. Computed using alpha = .05

b. R Squared = .982 (Adjusted R Squared = .980)

The results of the ANOVA main effects are now presented graphically in Figures 21 through 24 to illustrate the magnitude of each main effect on the total annual inventory cost.

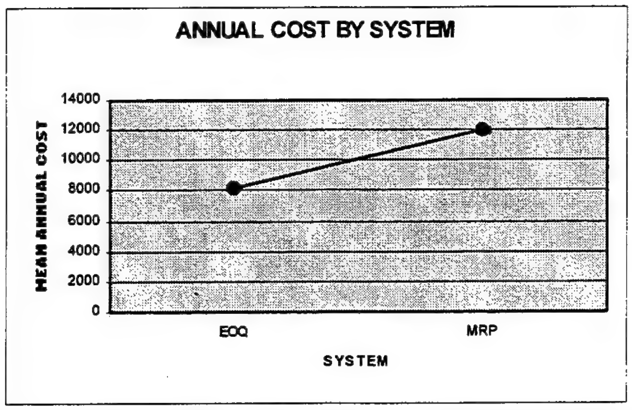


Figure 21: Main Effect of System on Annual Inventory Cost

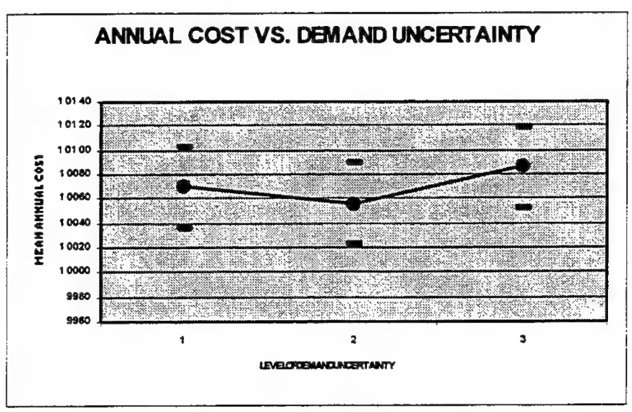


Figure 22: Main Effect of Demand Uncertainty on Annual Inventory Cost

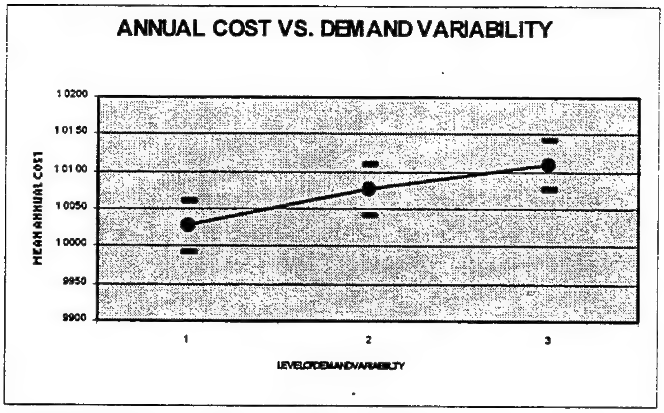


Figure 23: Main Effect of Demand Variability on Annual Inventory Cost

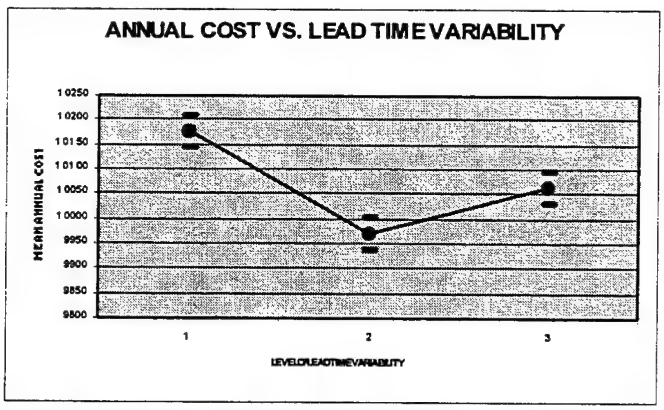


Figure 24: Main Effect of Lead Time Variability on Annual Inventory Cost

Tukey's Tests for Multiple Comparisons

Tukey's tests were again applied to gain insight into the significant factors and interaction effects identified in the ANOVA. The system appears to have a statistically and practically significant effect on the total inventory cost, but the remaining three factors have relationships that are less clear. The main effects are examined first in the following section.

Main Effects

The results of Tukey's test for the main effect of system on annual inventory cost are presented in Table 19 below. The mean costs of the two systems were found to be statistically different at the α=0.05 level. In addition, the two means show practical significance in that the MRP model has a mean annual inventory cost that is approximately 47 percent higher than that of the EOQ model.

Table 19: Tukey's Test for Main Effect of System on Annual Inventory Cost

```
TUKEY (HSD) COMPARISON OF MEANS OF ANN_COST BY SYS

                                HOMOGENEOUS
   SYS            MEAN          GROUPS
---------      ----------     -----------
    2             11978         I
    1            8163.3         .. I

ALL 2 MEANS ARE SIGNIFICANTLY DIFFERENT FROM ONE ANOTHER.

CRITICAL Q VALUE                     2.772    REJECTION LEVEL    0.050
CRITICAL VALUE FOR COMPARISON       45.699
STANDARD ERROR FOR COMPARISON       23.316

ERROR TERM USED: RESIDUAL, 486 DF
```

Results of the remaining three Tukey's tests are presented in Tables 20 through 22 below. The results are consistent with the ANOVA results, with all factors but demand uncertainty showing statistical significance.

Table 20: Tukey's Test for Main Effect of Demand Uncertainty on Annual Inventory Cost

```
TUKEY (HSD) COMPARISON OF MEANS OF ANN_COST BY D_UNC

                          HOMOGENEOUS
  D_UNC        MEAN       GROUPS
---------   ----------   -----------
     3         10086      I
     1         10070      I
     2         10056      I

THERE ARE NO SIGNIFICANT PAIRWISE DIFFERENCES AMONG THE MEANS.

CRITICAL Q VALUE                     3.314     REJECTION LEVEL    0.050
CRITICAL VALUE FOR COMPARISON       66.924
STANDARD ERROR FOR COMPARISON       28.557

ERROR TERM USED: RESIDUAL, 486 DF
```

Table 21: Tukey's Test for Main Effect of Demand Variability on Annual Inventory Cost

```
TUKEY (HSD) COMPARISON OF MEANS OF ANN_COST BY D_VAR

                          HOMOGENEOUS
  D_VAR        MEAN       GROUPS
---------   ----------   -----------
     3         10110      I
     2         10076      I I
     1         10027      .. I

THERE ARE 2 GROUPS IN WHICH THE MEANS ARE
NOT SIGNIFICANTLY DIFFERENT FROM ONE ANOTHER.

CRITICAL Q VALUE                     3.314     REJECTION LEVEL    0.050
CRITICAL VALUE FOR COMPARISON       66.924
STANDARD ERROR FOR COMPARISON       28.557

ERROR TERM USED: RESIDUAL, 486 DF
```

Table 22: Tukey's Test for Main Effect of Lead Time Variability on Annual Inventory Cost

```
TUKEY (HSD) COMPARISON OF MEANS OF ANN_COST BY LT_VAR

                          HOMOGENEOUS
  LT_VAR       MEAN       GROUPS
---------   ----------   -----------
     1        10177        I
     3        10064      .. I
     2        9971.2     .... I

ALL 3 MEANS ARE SIGNIFICANTLY DIFFERENT FROM ONE ANOTHER.

CRITICAL Q VALUE                   3.314     REJECTION LEVEL     0.050
CRITICAL VALUE FOR COMPARISON     66.924
STANDARD ERROR FOR COMPARISON     28.557

ERROR TERM USED: RESIDUAL, 486 DF
```

Demand variability shows statistically significant differences between the means of its levels 1 and 3, but the differences can be considered practically insignificant because of the small magnitude. Specifically, the absolute difference between levels 1 and 3 is just \$83, which can hardly be considered significant. Likewise, lead time variability shows statistically significant differences between all of its three levels, but the absolute difference is just \$206. The interesting result with regard to lead time variability is that the highest cost is associated with the lowest level of variability. Levels 2 and 3 show slightly lower costs, with level 2 the lowest of the three. This can probably be explained by the interaction between demand variability and lead time variability, which shows significance at the α=0.1 level. In terms of main effects of the factors on cost, then, the system is the only factor showing both statistical and practical significance.

Interaction Effects

Only one of the six first-order interactions were shown in the ANOVA to be statistically significant at $\alpha=0.05$ in terms of annual inventory cost: the interaction between lead time variability and system. The effects of system and lead time variability are depicted graphically in Figure 25 below.

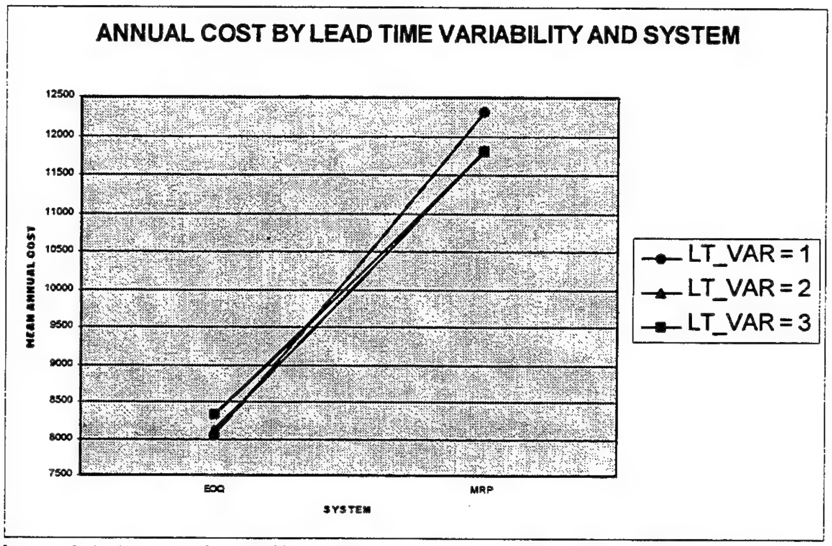


Figure 25: Interaction Effects Between Lead Time Variability and System

To gain more insight into the relationship between system and lead time variability, Tukey's tests were performed on the main effects of lead time variability within each system. The results are shown in Tables 23 and 24 below.

Table 23: Tukey's Test for Main Effect of Lead Time Variability on Annual Inventory Cost: EOQ

```
TUKEY (HSD) COMPARISON OF MEANS OF ANN_COST BY LT_VAR

                         HOMOGENEOUS
  LT_VAR      MEAN       GROUPS
 ---------  ----------  -----------
     3        8321.4     I
     2        8123.0    .. I
     1        8045.4    .... I

ALL 3 MEANS ARE SIGNIFICANTLY DIFFERENT FROM ONE ANOTHER.

CRITICAL Q VALUE                      3.314    REJECTION LEVEL    0.050
CRITICAL VALUE FOR COMPARISON        74.552
STANDARD ERROR FOR COMPARISON        31.812

ERROR TERM USED: RESIDUAL, 243 DF
```

Table 24: Tukey's Test for Main Effect of Lead Time Variability on Annual Inventory Cost: MRP

```
TUKEY (HSD) COMPARISON OF MEANS OF ANN_COST BY LT_VAR

                         HOMOGENEOUS
  LT_VAR      MEAN       GROUPS
 ---------  ----------  -----------
     1         12309     I
     2         11819    .. I
     3         11806    .. I

THERE ARE 2 GROUPS IN WHICH THE MEANS ARE
NOT SIGNIFICANTLY DIFFERENT FROM ONE ANOTHER.

CRITICAL Q VALUE                      3.314    REJECTION LEVEL    0.050
CRITICAL VALUE FOR COMPARISON        111.16
STANDARD ERROR FOR COMPARISON        47.434

ERROR TERM USED: RESIDUAL, 243 DF
```

Two items of interest arise in the results of Tables 23 and 24 above. First, the effect of lead time variability on annual inventory cost is more pronounced in the EOQ model. All three means are significantly different in the latter, whereas two of the means are grouped together in

the MRP model. The second point of interest is that the high level of variability is associated with the highest cost in the EOQ model, while associated with the lowest cost in the MRP model. This result is counterintuitive, and should therefore be viewed with caution. In terms of practical significance, however, the differences in total cost are all below about 500 dollars, so that even the largest difference is relatively inconsequential.

Summary of Results Using Annual Inventory Cost as the Dependent Variable

Using annual inventory cost as the dependent variable yielded different results than those found using AWP days. In both cases, the system was the most significant determining factor in the overall performance. In the present case, however, the results favor the EOQ model as more cost effective than the MRP model. Annual inventory costs were significantly higher using the latter. The remaining three factors, even those that showed statistical significance, showed little practical significance. The magnitude of the differences within these factors was small in relation to the system factor, which should be expected given the robustness of the EOQ model in terms of cost.

Summary: Tying the Performance Measures Together

Because of the nature of inventory systems, it is common to find that trade-offs are necessary between material availability and cost. Many studies have therefore included a holistic measure that attempts to tie two or more performance measures of interest together into an overall performance measure. In the present study, a "relative performance index (RPI)" has been developed to that end. The RPI is defined as the overall performance of a system relative to the performance of the baseline system in the study, and is given by equation (18):

$$RPI_j = \frac{\sum_{i=1}^{N} w_i(P_{ij}/P_{0j})}{N} \tag{18}$$

Where: RPI_j = RPI for system j
P_{ij} = Value of performance measure *i* for system *j*
P_{io} = Value of performance measure *i* for baseline system
W_i = Relative weight assigned to performance measure *i*
N = Number of performance measures being integrated

For most inventory performance measures, lower values are desirable. For example, costs, number of backorders, and AWP days are sought to be minimized. The RPI as written in equation (18) is therefore useful only if all measures follow this convention. If measures such as fill rate are used, where larger values are desirable, then the inverse of P_{ij} / P_{oj} must be used. It should be noted that the RPI for the baseline system will always be equal to one. Therefore, an RPI_j that is greater than 1, in this study, indicates lower performance levels than the baseline, while an RPI_j that is less than 1 indicates higher performance levels than the baseline. Table 25 below summarizes the components of equation (18) for the present study using the overall average results.

Table 25: RPI Components

SYSTEM	**MEAN AWP**	P_{1j} / P_{10}	**MEAN COST**	P_{2j} / P_{20}
EOQ (baseline)	15.854	1	8,163	1
MRP	1.396	0.0881	11,978	1.4674

Substituting the values from Table 25 into equation (18), and assuming equal weights for both performance measures:

$$RPI_{MRP} = (0.0881 + 1.4674) / 2$$

$$= 0.78$$

By integrating the two performance measures using equation (18), the performance of the MRP model has outperformed the EOQ model by about 22 percent. For a more accurate measure based on cost-based weighting, a daily cost associated with "AWP days" would need to be determined.

To gain deeper insight into the relative performance of MRP, a similar analysis was conducted for each of the three factors in this study. The results are summarized in Table 26 below.

Table 26: RPI by Factor

FACTOR	LEVEL	RPI
1	1	0.761068
	2	0.761726
	3	0.764141
2	1	0.756206
	2	0.765324
	3	0.765405
3	1	0.766876
	2	0.746771
	3	0.773289

From the results in Table 26, it appears that there is an interaction between MRP's relative performance and lead time variability (Factor 3), while factors 1 and 2 indicate no interaction. The results of all individual replications are now displayed graphically in Figures 26 through 28 to gain more insight into the relationship.

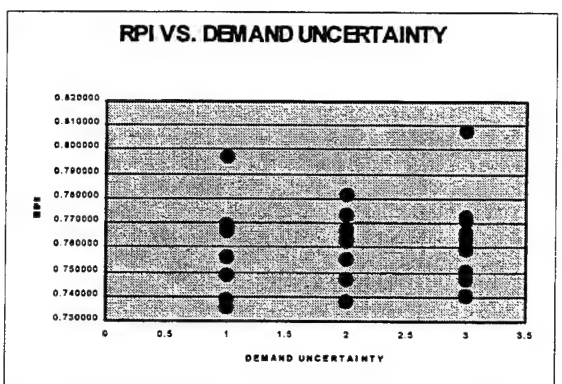


Figure 26: RPI vs. Demand Uncertainty - MRP

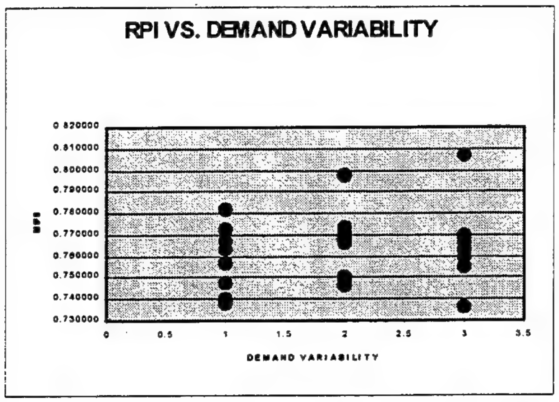


Figure 27: RPI vs. Demand Variability - MRP

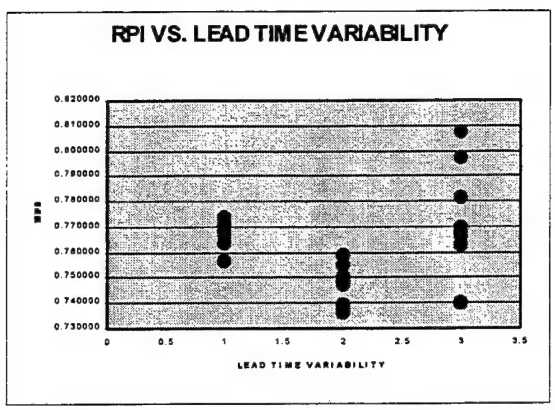


Figure 28: RPI vs. Lead Time Variability - MRP

The graphical results in Figures 26 through 28 are consistent with the results in Table 26, in that there appears to be some interaction between RPI and lead time variability. To formalize the analysis, ANOVA was performed on all three factors with RPI as the dependent variable. The results are shown in Table 27 below.

Table 27: ANOVA for RPI vs. Factors 1, 2, and 3

ANALYSIS OF VARIANCE TABLE FOR RPI

SOURCE	DF	SS	MS	F	P
D_UNC (A)	2	4.714E-05	2.357E-05	0.09	0.9139
D_VAR (B)	2	5.033E-04	2.516E-04	0.97	0.4190
LT_VAR (C)	2	0.00345	0.00172	6.65	0.0199
A*B	4	7.945E-04	1.986E-04	0.77	0.5756
A*C	4	2.752E-04	6.879E-05	0.27	0.8920
B*C	4	1.775E-04	4.437E-05	0.17	0.9470
A*B*C	8	0.00207	2.590E-04		
TOTAL	26	0.00732			

Again, the effect of lead time variability is the only factor showing significance. As a final step, Tukey's test for multiple comparisons was performed for the mean RPI for each level of lead time variability. The results are shown in Table 28.

Table 28: Tukey's Test for Mean of RPI by Lead Time Variability

TUKEY (HSD) COMPARISON OF MEANS OF RPI BY LT_VAR

LT_VAR	MEAN	HOMOGENEOUS GROUPS
3	0.7733	I
1	0.7669	I I
2	0.7468	.. I

THERE ARE 2 GROUPS IN WHICH THE MEANS ARE NOT SIGNIFICANTLY DIFFERENT FROM ONE ANOTHER.

CRITICAL Q VALUE	4.034	REJECTION LEVEL	0.050
CRITICAL VALUE FOR COMPARISON	0.0216		
STANDARD ERROR FOR COMPARISON	7.586E-03		

From the results discussed above, lead time variability appears to have a statistically significant effect on the performance of MRP relative to EOQ. The nature of that effect is consistent with earlier findings, in that the performance is stable across the lower two levels of lead time variability, but begins to deteriorate at level 3. Again, a study of the "break-even point" is left for future research.

V. Conclusions and Recommendations

Introduction

With the theoretical foundation laid in Chapter II, Chapters III and IV attempted to apply the existing inventory management knowledge to a problem currently being experienced in the Air Force. An experiment was conducted in order to answer the research questions identified in Chapter I of this report, with the ultimate goal of shedding more light on the issue of MRP usage in a remanufacturing environment. This chapter now ties the findings of previous chapters together to answer the research questions. These questions are individually and separately addressed below. Following the discussion of the research questions, additional findings are discussed that, although not directly tied to the present research, are important from a theoretical standpoint to the body of existing research. Finally, recommendations for future research are presented.

Conclusions

Each of the four research questions from Chapter I is now restated and addressed based on the information contained in Chapters II through IV.

1. *Does the EOQ model adequately meet the needs of the Air Logistics Centers in ensuring consumable parts availability?*

In Chapter II, the issue of the performance of the EOQ model in the DoD was addressed at length. The EOQ model is considered very robust in terms of the total annual inventory cost it attempts to minimize. That is, even if there are deviations from the model's assumptions, the total annual inventory cost remains relatively constant. Its reliance on average past demand dampens much of the variability usually associated with inventory requirements, so on average it performs adequately in terms of material availability as well. Upon closer examination, however, it has become apparent that it performs very poorly for a certain percentage of consumable parts in the DoD. The DRC study cited in Chapter II illustrated that, despite its robustness, the EOQ model

has a tendency to allow certain items to "slip through the cracks," thereby creating inventory excesses and shortages throughout the organization. The implications are obvious. Excess inventory carries with it an increase in holding cost, while shortages can delay maintenance actions on vital weapon systems. The DRC study showed that the majority of backordered items are inventory anomalies that have uncharacteristic demand histories for one reason or another.

Getting back to the research question at hand, the EOQ model does adequately meet the needs of the ALCs *in most cases*. The problem, then, lies in the fact that there are a handful of cases where it does not meet the needs of the ALCs, and these cases tend to be those that hold up end-item production. Clearly, the EOQ model is not entirely without merit. It does, however, require some level of additional help to make it effective. At base level, this help traditionally comes in the form of exception management in the Stock Control and Mission Capable (MICAP) Elements of Base Supply. This process is primarily manual and time-intensive, however. The scope of inventory at the ALCs makes such manual manipulation difficult at best. At worst, it becomes impossible to adequately identify those items that will "fall through the cracks" in sufficient time to avoid production delays. It is exactly this shortfall of the EOQ model for which RFM was designed to compensate.

2. Would the use of Material Requirements Planning improve inventory availability?

Chapter II also provided an extensive theoretical foundation in the area of Material Requirements Planning. The literature has identified a number of factors affecting the performance of MRP in practice. Among these are product structure, demand variability and uncertainty, lead time variability, costs, and lot-sizing rule. Most studies have concluded that MRP can be expected to outperform most independent demand systems over a wide range of experimental conditions. The present study attempted to fill a gap in the literature in the area of MRP use in a remanufacturing environment. As noted in Chapter II, the unique conditions of a repair operation raise the question of MRP utility in such an environment. At the heart of the

matter, a repair operation experiences a great deal more demand variability then does the traditional manufacturing operation. Jacobs and Whybark concluded that " a very perverse environment is needed before the preference [for reorder point policies like the EOQ] can be argued on inventory efficiency grounds" (Jacobs and Whybark, 1992: 341). The question addressed in the present study then is whether or not the ALCs represent that "perverse environment."

The simulation results discussed in Chapter IV indicate that the ALCs, despite the high degree of variability they experience in demand and lead times, are not "perverse" enough to break down MRP performance. Although the cost performance of MRP was poor compared to EOQ, its material availability performance outweighs this shortfall as measured by the Relative Performance Index developed in Chapter IV. So the answer to the research question, based on the results of this study, must be a tentative "yes."

Care must be taken in drawing concrete conclusions based on the results of one study, however. The present study used a simplified product structure, for example, where previous research has suggested that product structure is a significant determinant of MRP performance. Every effort was made to capture the full range of variability and uncertainty experienced in the repair process of the ALCs, but there are no doubt additional sources that warrant research. Finally, the "inventory anomalies" that break down the EOQ model's effectiveness have not been adequately captured by the simulation model. In general, the successful implementation of an MRP system is an extremely costly and time-consuming process with implications at the very core of the corporate culture. The decision to fully implement such a system, then, should be made only after exhaustive research that falls beyond the limited scope of this study. The limitations above are addressed at the end of this chapter as recommendations for future research, but for now are presented merely as cautions to the reader that the results should be taken in full context.

3. *Can RFM be assumed to perform at the same level as MRP, given their similarities and differences?*

The answer to research question 3 must be a resounding "yes." RFM directly uses MRP logic, so insofar as MRP performs well by given measures in a given environment, RFM will perform to approximately the same level. Given that, it should be reiterated that RFM is not a full-scale MRP system. RFM can be described as a "poor man's" MRP system that takes advantage of MRP's forward-look capability, without the time-consuming and expensive leap to full MRP. This concept is addressed in more detail in the answer to research question 4 below.

4. *What procedural measures are necessary to ensure RFM's success?*

CACI's RFM system represents an interesting theoretical direction for inventory management. Traditionally, studies have pitted competing theories against one another and attempted to determine which is superior by selected measures. In this regard, the present study is no exception. What RFM represents, in contrast, is a system that draws from the advantages of one theory to temper the disadvantages of another. RFM, in essence, provides the user with an advance look of future inventory problems. As already noted, these problems generally appear as exceptions or anomalies. It has been shown that the EOQ model does not adequately detect these exceptions in time to fix the problems, and so RFM can be considered a cost-effective way to do just that.

In answering the research question above, several issues warrant discussion. First, users of RFM must be fully aware of its intended use. Because of the magnitude of inventory shortages experienced in an ALC environment over the years, the inclination toward accepting RFM as a panacea to solve all inventory problems is a very real possibility. This blind faith must be avoided. Users at all levels need to be made aware of the benefits and weaknesses of MRP logic, particularly as they relate to a repair environment. Only with a full understanding of potential pitfalls can the pitfalls be avoided.

A second important point will be discussed in more detail in the following section, and relates to the selection of a lot-sizing rule for RFM-initiated orders. The pilot runs of the simulation model initially ordered on a weekly basis using the lot-for-lot sizing technique. In essence, the exact number of items projected were ordered a lead time prior. The performance of MRP was extremely poor by both measures using lot-for-lot, prompting a change to the EOQ lot-sizing technique. The lesson learned is that in a depot repair environment, RFM orders should be placed for the economic order quantity. If no EOQ is available for an item, as is often the case with the anomalies being referred to, an estimate of the EOQ should be developed and used. That said, the cost performance of the RFM orders can be expected to be poor relative to the EOQ orders. This leads to the third and final point that RFM orders should be placed only in those cases where the EOQ model is seen to be inadequate, and should be continually reviewed by inventory professionals. If implemented with care, RFM shows promise as a new approach to inventory management at the ALCs.

Additional Findings

In addition to the findings related to the research questions, several findings were noted in Chapter IV that add to the body of existing literature. The first is that MRP generally outperforms EOQ in terms of inventory efficiency. This confirms most of the existing research on the subject (Jacobs and Whybark, 1992; Grasso and Taylor, 1984; Axsater and Rosling, 1994; Long and Engberson, 1994). The second confirmatory finding relates to the effect of lead time variability on MRP performance. In Chapter IV, it was noted that lead time variability was a significant factor in both MRP and EOQ performance. Furthermore, it interacted significantly in both cases with other factors. This result confirms the work of Brennan and Gupta, who concluded that lead time variability showed so much significance both in main and interaction effects that its reduction should be made a top priority in firms employing MRP systems (Brennan and Gupta, 1993: 1706).

One result that appears counterintuitive is the relative insignificance of demand uncertainty. This can probably be explained, at least partially, by the fact that the end-item uncertainty in an ALC environment is relatively minor. Production schedules are usually negotiated well in advance of production, and relatively minor changes are usually experienced following negotiation. The component of uncertainty that relates to the piece-part uncertainty was "hard-wired" into the model, and so was not varied and measured at different levels. To fully test the effects of demand uncertainty, the results of this study could be duplicated assuming a deterministic replacement of parts. For example, instead of the quantity of a particular part needed to repair a reparable being drawn from a distribution, it would be set at a discrete number. This would approximate the traditional manufacturing environment and its associated uncertainty, and would allow a direct comparison with On-Condition Maintenance repair environments.

Recommendations for Future Research

Several opportunities surfaced during the course of this study which lend themselves to additional follow-on research. The first and most obvious is an expansion of the simulation model to include a larger and more representative product structure. The model could also be used to test additional levels of the factors already tested. Particularly in the case of lead time variability, the results of the present study were somewhat inconclusive. In order to validate the lead time variability effect, higher levels of the factor need to be tested. Additionally, the model needs to be "pushed" further to determine the cause for MRP's high cost structure. A possible cause is the lot-sizing technique used, which is therefore a logical additional factor to include in future research. In this way, the results of this study could be validated and expanded, with additional inferences possibly arising. An extension of this idea would be to develop a cost weighting method to more accurately determine the relationship of the performance of the two systems. In doing so, a cost basis for AWP days would need to be determined.

Another logical study stemming from the present one is a comparison study of MRP in a traditional manufacturing setting versus the same in a repair setting. Utilizing the same factors and levels, but removing the piece-part uncertainty inherent in the repair process, would serve to quantify the magnitude of the effect of this distinct environment on MRP performance. With the going interest in MRP use for DoD applications, this would be both useful and relevant.

A third possible research area is that of time-series analysis on RFM's effectiveness. With RFM now installed and being used at two ALCs, San Antonio and Oklahoma City, it will be possible to sample RFM assessments at points in time and test its effectiveness in predicting future requirements. Again, this is a logical next step in ensuring that RFM performs adequately well to justify its use for ordering parts.

Finally, a detailed analysis of the material "anomalies" referred to in this report would be helpful. Since it has been identified that the EOQ model performs poorly for this select group of items, it is important to further identify the reasons for this poor performance and the characteristics of the items that cause it. Only with this deeper understanding can the EOQ model be modified to provide optimal performance.

Summary

The present study has attempted to test the MRP model in an Air Force repair environment. Although a great deal of research exists on MRP, little has been done to test its use in the distinct case of remanufacturing. Under the increased levels of variability and uncertainty characteristic of this environment, MRP showed strong performance relative to the EOQ model in terms of material availability, while its cost performance was relatively poor. When both performance measures are considered together, however, MRP outperformed EOQ in the context of this experiment. The limitations of this study have been discussed in the context of both the results and their implications, and future research has been suggested to further validate the findings.

Appendix A: Transformation of Source Data

Bill of Materials

The data in this appendix were provided by the OC-ALC Propulsion Directorate, and were used to formulate the parts used in the simulation model. Table 29 shows a list of all level 1 parts associated with the TF-33 high speed compressor. The data elements in the table are defined as follows:

LVL	Indenture Level (=1 for all parts shown; =0 for compressor)
P/S	P = Prime S = Substitute A = Alternate
Part Number	Self-explanatory
Noun	Item Name
NSN	National Stock Number
Stock Price	Unit Cost of Item
UPA	Units Per Next Higher Assembly
REPL %	Replacement Percentage

Table 29: TF-33 High Speed Compressor Level 1 Parts Data

LVL	P/S	PART NUMBER	NOUN	NSN	STOCK PRICE	UPA	REPL %
0		770645	HIGH SPEED COMPR	2840009188399RV	$231,583.32	1	
1	S	534229CL4	COUNTER WEIGHT	3040009440087RV	$0.73	1	0.01
1	S	534229CL3	COUNTER WEIGHT	3040009440086RV	$2.78	1	0.01
1	S	534229CL2	COUNTER WEIGHT	3040009218626RV	$1.50	1	0.01
1	P	534229CL1	COUNTER WEIGHT	3040009440084RV	$1.61	16	0.02
1	S	502281CL9	COUNTER WEIGHT	3040009480994RV	$3.26	1	
1	S	502281CL8	COUNTER WEIGHT	3040000792512RV	$8.46	1	0.02
1	S	502281CL7	COUNTER WEIGHT	3040004423632RV	$7.50	1	
1	S	502281CL6	COUNTER WEIGHT			1	
1	S	502281CL5	COUNTER WEIGHT			1	
1	S	502281CL4	COUNTER WEIGHT	3040004776893RV	$2.32	1	
1	S	502281CL3	COUNTER WEIGHT	3040004776891RV	$12.24	1	
1	S	502281CL2	COUNTER WEIGHT	3040004776890RV	$6.32	1	0.02
1	P	502281CL1	COUNTER WEIGHT	3040004423631RV	$8.94	16	
1	S	457297P40	SEAL RING	5330011048539RV	$19.31	2	0.50
1	S	457297P30	SEAL RING	5330011048538RV	$21.15	2	0.50
1	S	457297P20	SEAL RING	5330007622371RV	$26.18	2	0.70

LVL	P/S	PART NUMBER	NOUN	NSN	STOCK PRICE	UPA	REPL %
1	S	457297P10	SEAL RING	5330007622370RV	$8.07	2	0.50
1	S	358195CL8	COUNTER WEIGHT	3040006748602RV	$1.17	1	1.10
1	S	358195CL7	COUNTER WEIGHT	3040006748601RV	$3.86	1	1.10
1	S	358195CL6	COUNTER WEIGHT	3040006715950RV	$4.19	1	1.10
1	S	358195CL5	COUNTER WEIGHT	3040006715949RV	$8.13	1	1.10
1	S	358195CL4	COUNTER WEIGHT	3040006746398RV	$5.70	1	1.10
1	S	358195CL3	COUNTER WEIGHT	3040006746398RV	$4.80	1	0.03
1	S	358195CL2	COUNTER WEIGHT	3040006746397RV	$2.03	1	1.10
1	S	358195CL1	COUNTER WEIGHT	3040006746399RV	$1.29	1	1.10
1	S	211146CL9	COUNTER WEIGHT	3040003965100RV	$4.70	1	0.03
1	S	211146CL8	COUNTER WEIGHT	3040003965099RV	$2.71	1	0.02
1	S	211146CL7	COUNTER WEIGHT	3040003965098RV	$6.10	1	0.05
1	S	211146CL6	COUNTER WEIGHT	2840003965097FN		1	
1	S	211146CL5	COUNTER WEIGHT	3040003965096RV	$0.28	1	
1	S	211146CL4	COUNTER WEIGHT	3040003965095RV	$0.28	1	
1	S	211146CL3	COUNTER WEIGHT	3040003965094RV	$1.07	1	
1	S	211146CL2	COUNTER WEIGHT	3040003965093RV	$9.62	1	
1	P	211146CL1	COUNTER WEIGHT	3040003965092RV	$115.26	30	
1	A	794724	9TH STG AIRSEAL	2840012291009RV	$913.25	1	0.24
1	P	794312	12TH STG DISK	2840012291036RV	$9,359.52	1	0.80
1	P	794311	11TH STG DISK	2840012291035RV	$7,483.82	1	0.70
1	P	794310	10TH STG DISK	2840012291037RV	$9,074.94	1	0.80
1	S	789413	13TH STG DISK			1	
1	S	787216	16TH STG DISK			1	
1	A	785514	14TH STG DISK			1	
1	P	770624	10TH STG SPACER	2840010401901RV	$1,760.60	1	0.20
1	P	770620	11TH STG SPACER	2840010401900RV	$2,150.16	1	0.27
1	P	766595	15TH STG STATOR	2840010045772RV	$29,845.49	1	0.85
1	P	766594	14TH STG STATOR	2840010045773RV	$28,239.19	1	0.84
1	P	766593	13TH STG STATOR	2840010051882RV	$26,716.37	1	0.83
1	P	765192	12TH STG STATOR	2840010045774RV	$6,182.34	1	0.88
1	P	765191	11TH STG STATOR	2840010045771RV	$4,983.31	1	0.84
1	P	765190	10TH STG STATOR	2840010041802RV	$5,294.45	1	0.93
1	P	753213	13TH STG BLADE	2840001662357RV	$146.71	75	0.35
1	P	753212	12TH STG BLADE	2840001662356RV	$161.89	75	0.35
1	P	753211	11TH STG BLADE	2840002224164RV	$148.62	75	0.27
1	P	753116	16TH STG BLADE	2840009819204RV	$143.34	77	0.15
1	P	753110	10TH STG BLADE	2840011606478RV	$156.84	73	0.12
1	P	753015	15TH STG BLADE	2840008216301RV	$141.66	85	0.40
1	P	753014	14TH STG BLADE	2840008224834RV	$131.29	85	0.30
1	S	748893	13TH STG STATOR	2840010051882RV	$16,928.89	1	
1	S	730794	14TH STG STATOR	2840009668059RV	$28,239.19	1	0.57
1	S	730793	13TH STG STATOR	2840009668058RV	$26,716.37	1	0.87
1	S	730675	15TH STG STATOR	2840009668060RV	$29,845.49	1	0.45
1	S	730670	10th STG STATOR	2840009086065RV	$5,294.45	1	0.90
1	P	729583	9TH STG AIRSEAL	2840009663008RV	$514.00	1	
1	S	726713	13TH STG BLADE	2840001662357RV	$146.71	75	
1	S	726712	12TH STG BLADE	2840001662356RV	$161.89	75	0.35
1	S	716111	11TH STG BLADE	2840002224164RV	$148.62	75	0.27
1	S	713316	16TH STG BLADE	2840009819204RV	$48.52	77	
1	S	711515	15TH STG BLADE	2840008216301RV	$41.85	85	
1	S	711514	14TH STG BLADE	2840008224834RV	$77.84	85	
1	S	711310	10TH STG BLADE	2840009477113RU	$60.06	73	
1	*P	710413	HUB REAR, H/S	2840009113075RV	$8,030.22	1	0.16

LVL	P/S	PART NUMBER	NOUN	NSN	STOCK PRICE	UPA	REPL %
1	S	704284	14TH STG STATOR	2840009668059RV	$17,952.31	1	
1	S	704283	13TH STG STATOR	2840009668058RV	$26,716.37	1	0.42
1	S	704282	12TH STG STATOR	2840009993295RV	$8,023.09	1	
1	S	704170	10th STG STATOR	2840009086065RV	$6,211.29	1	
1	S	703610	10th STG DISK	2840009819211RV	$9,074.94	1	0.11
1	A	702412	12th STG DISK	2840009819209RV	$9,359.52	1	
1	A	702411	11th STG DISK	2840009819210RV	$7,483.82	1	0.23
1	A	702410	10TH STG DISK	2840012223112RV	$9,074.94	1	1.00
1	P	676013	LOCK-CPRSR BLADE	2840004356880 RV	$2.18	75	0.90
1	P	674942	LOCK-CPRSR BLADE	2840008836001 RV	$13.87	85	1.02
1	P	674941	LOCK-CPRSR BLADE	2840008835968 RV	$1.06	85	1.00
1	P	674939	LOCK-CPRSR BLADE		$0.71	75	1.00
1	P	657916	16TH STG DISK	2840002430367RV	$8,865.84	1	
1	P	657915	15TH STG DISK	2840002430363RV	$5,121.29	1	1.00
1	P	657914	14TH STG DISK	2840002430362RV	$12,616.38	1	1.00
1	P	657913	13TH STG DISK	2840002430356RV	$11,098.62	1	1.00
1	P	636592	PLUG	2840001106048RV	$6.03	4	
1	P	553365	SEAT #4 BRG SEAL	2840009871695RV	$866.39	1	0.05
1	P	542046	HUB-FRONT, H/S	2840009111035RV	$9,928.69	1	0.24
1	S	528251	HUB REAR, H/S	2840009113075RV	$8,008.10	1	
1	P	516924	LOCK-CPRSR BLADE	2840009626580RV	$0.86	75	1.45
1	P	516923	LOCK-CPRSR BLADE	2840009626751RV	$0.90	73	1.11
1	S	512271	11TH STG STATOR	284009086059RV	$7,412.75	1	
1	S	512270	10TH STG STATOR	2840009086065RV	$4,749.42	1	
1	P	506955	NUT #4 BRG INNER	5310009183921RV	$250.60	1	0.14
1	A	506511	11TH STG BLADE	2840009477114RV	$34.41	75	
1	S	506510	10TH STG BLADE	2840009477113RU	$60.06	73	
1	P	495875	TIERODS-REAR COMPR	2840009621254RV	$61.86	16	
1	S	494422	LOCK-CPRSR BLADE	2840007596321RU	$0.18	85	
1	P	494420	LOCK-CPRSR BLADE	2840007596319 RV	$1.61	77	1.10
1	P	484641	SLEEVE-DRIVE SHAFT	2840009668107RV	$1,401.53	1	0.05
1	P	483168	PIN-SHLDR,HDLS	5315000787322RV	$1.23	8	0.40
1	S	483166	9TH STG AIRSEAL	2840009663008RV	$514.00	1	0.24
1	P	482461	CASE,REAR COMPRS	2840009663003RV	$5,404.49	1	0.04
1	S	476675	15TH STG STATOR	2840009668060RV	$29,845.49	1	
1	S	468799	HUB REAR, H/S	2840009800740RV	$8,030.22	1	
1	S	464214	14TH STG BLADE	2840008224834RV	$131.29	85	0.30
1	P	461485	15TH STG SPACER	2840009913735RV	$1,381.16	1	0.10
1	P	461484	14TH STG SPACER	2840009875798RV	$1,339.42	1	0.40
1	P	461483	13TH STG SPACER	2840009913734RV	$1,637.92	1	0.25
1	P	461482	12TH STG SPACER	2840009875802RV	$1,486.14	1	0.52
1	A	461481	11TH STG SPACER	2840009875801RV	$2,150.16	1	
1	A	461480	10TH STG SPACER	2840009913733RV	$2,477.09	1	
1	P	457297	SEAL RING	5330009783012RV	$16.61	2	0.97
1	A	457215	15TH STG DISK	2840009819206RV	$5,121.29	1	
1	A	457214	14TH STG DISK	2840009819207RV	$12,616.38	1	
1	S	457213	13TH STG DISK	2840009831166RV	$9,670.66	1	
1	S	457212	12th STG DISK	2840009819209RV	$9,359.52	1	
1	S	457211	11th STG DISK	2840009819210RV	$7,483.82	1	
1	S	457210	10TH STG DISK	2840009819211RV	$8,778.02	1	
1	S	454381	11TH STG STATOR	284009819215RV	$4,983.31	1	
1	S	454380	10TH STG STATOR	2840009819217RV	$5,294.45	1	
1	P	413923	WASHER-KEY	5310007878026RV	$0.58	16	1.14

LVL	P/S	PART NUMBER	NOUN	NSN	STOCK PRICE	UPA	REPL %
1	P	375770	NUT/SORT: SILVER	5310008043092RV	$4.07	16	0.35
1	A	375411	11TH STG BLADE	2840006717814RV	$148.62	75	
1	S	375410	10TH STG BLADE	2840006717813RV	$156.84	73	
1	S	248150	LOCK-CPRSR BLADE	2840000983007RV	$0.84	75	0.02
1	S	248148	LOCK-CPRSR BLADE	2840000983005RV	$1.61	73	1.02
1	S	215315	15TH STG BLADE	2840008216301RV	$141.66	85	0.10
1	S	215314	14TH STG BLADE	2840003965194RV	$131.29	85	0.45
1	A	172257	NUT #4 BRG INNER	5310003109270RV	$78.69	1	
2	P	528254	BUSHING	3120009100381RV	$237.07	1	0.36

Repair Times

Table 30 below is an example showing the aggregated historical flow days and associated summary statistics for all prime, substitute, and alternate 10th Stage Disks. Similar historical data were provided for each level 1 reparable part in the high speed compressor, but are omitted here for brevity. Summary statistics for all parts, however, are provided in Table 31.

Table 30: Sample Flow Day Data and Summary Statistics for 10th Stage Disk

NOUN	WCD	FLOW DAYS
10TH STG DISK H/S	33440N	38.1
10TH STG DISK H/S	33440N	4.2
10TH STG DISK H/S	33440N	21.3
10TH STG DISK H/S	33440N	6
10TH STG DISK H/S	33440N	15.2
10TH STG DISK H/S	33442N	0.8
10TH STG DISK H/S	33442N	3
10TH STG DISK H/S	33442N	3.3
10TH STG DISK H/S	33442N	5.3
10TH STG DISK H/S	33440N	14
10TH STG DISK H/S	33442N	25.3
10TH STG DISK H/S	33442N	27.7
10TH STG DISK H/S	33442N	27.7
10TH STG DISK H/S	33440N	50.2
10TH STG DISK H/S	33440N	7
10TH STG DISK H/S	33440N	8.2
10TH STG DISK H/S	33442N	7
10TH STG DISK H/S	33440N	8.1
10TH STG DISK H/S	33442N	14.2
10TH STG DISK H/S	33442N	21

10TH STG DISK H/S SUMMARY STATISTICS	
Mean	27.4648649
Standard Error	6.67801536
Median	14.1
Mode	27.7
Standard Deviation	40.6207816
Sample Variance	1650.0479
Kurtosis	7.18069608
Skewness	2.76348035
Range	170.9
Minimum	0.8
Maximum	171.7
Sum	1016.2
Count	37

NOUN	WCD	FLOW DAYS
10TH STG DISK H/S	33442N	25.2
10TH STG DISK H/S	33440N	163.9
10TH STG DISK H/S	33440N	171.7
10TH STG DISK H/S	33440N	122
10TH STG DISK H/S	33440N	71
10TH STG DISK H/S	33440N	10.2
10TH STG DISK H/S	33440N	11.1
10TH STG DISK H/S	33440N	11.1
10TH STG DISK H/S	33440N	14.1
10TH STG DISK H/S	33440N	14.9
10TH STG DISK H/S	33440N	27.9
10TH STG DISK H/S	33440N	1.2
10TH STG DISK H/S	33440N	9.1
10TH STG DISK H/S	33440N	12
10TH STG DISK H/S	33440N	13
10TH STG DISK H/S	33440N	14.2
10TH STG DISK H/S	33440N	16

Table 31: Summary Statistics for Flow Day Data

	10TH STG BLADE	10TH STG DISK	10TH STG SPACER	10TH STG STATOR
Mean	55.45882353	27.46486486	67.88333333	13.83946488
Standard Error	7.535026342	6.678015359	22.60140166	1.92090921
Median	56.9	14.1	29.5	6.2
Mode	#N/A	27.7	14	4
Standard Deviation	31.0677095	40.6207816	135.60841	33.21562533
Sample Variance	965.2025735	1650.047898	18389.64086	1103.277766
Kurtosis	-0.084669911	7.180696082	30.70173139	40.77509294
Skewness	0.254752855	2.763480347	5.364227439	5.904912448
Range	118.9	170.9	820.8	310.9
Minimum	3.9	0.8	9.9	0.7
Maximum	122.8	171.7	830.7	311.6
Sum	942.8	1016.2	2443.8	4138

Count	17	37	36	299

	11TH STG BLADE	11TH STG DISK	11TH STG SPACER	11TH STG STATOR
Mean	32.46	37.97058824	54.42222222	18.35886792
Standard Error	3.541443522	7.572315099	9.260280855	2.859927294
Median	36.3	22.45	44.9	5.2
Mode	14.1	21.9	#N/A	2.2
Standard Deviation	11.19902774	44.15380508	48.1178308	46.55624334
Sample Variance	125.4182222	1949.558503	2315.325641	2167.483794
Kurtosis	-0.256150779	4.73181722	4.368839961	21.59625233
Skewness	-0.809947119	2.351756996	1.810971529	4.427821881
Range	33.9	182.5	218.2	377.5
Minimum	14.1	5.1	3	0.7
Maximum	48	187.6	221.2	378.2
Sum	324.6	1291	1469.4	4865.1
Count	10	34	27	265

	12TH STG BLADE	12TH STG DISK	12TH STG SPACER	12TH STG STATOR
Mean	69.83478261	43.2	43.92368421	11.39285714
Standard Error	24.74831939	9.633593999	6.473491118	1.657021224
Median	30.9	34.8	24.6	6.1
Mode	34.4	#N/A	14	6.1
Standard Deviation	118.6887703	48.16796999	56.43458719	28.41199544
Sample Variance	14087.02419	2320.153333	3184.862632	807.2414846
Kurtosis	11.97509356	5.526368263	24.0407077	88.30026186
Skewness	3.36694296	2.186648996	4.227411017	8.441772172
Range	531	209	408.1	361.3
Minimum	9.1	2.2	2.9	0.7
Maximum	540.1	211.2	411	362
Sum	1606.2	1080	3338.2	3349.5
Count	23	25	76	294

	13TH STG BLADE	13TH STG DISK	13TH STG SPACER	13TH STG STATOR
Mean	77.35217391	43.83076923	125.5592593	19.35019157
Standard Error	16.72300948	15.67823653	36.25712397	2.633033628
Median	42.1	21.3	48.6	5.9
Mode	25.1	14.9	#N/A	1
Standard Deviation	80.20073605	56.52868571	188.3975426	42.53796008
Sample Variance	6432.158063	3195.492308	35493.63405	1809.478048
Kurtosis	1.728342172	5.120418665	9.675313448	45.51094036
Skewness	1.659704489	2.351551456	2.937476452	5.511298812
Range	296.3	199.9	870	458.9
Minimum	1.7	1.2	4	0.7
Maximum	298	201.1	874	459.6
Sum	1779.1	569.8	3390.1	5050.4
Count	23	13	27	261

	14TH STG BLADE	14TH STG DISK	14TH STG SPACER	14TH STG STATOR
Mean	26.4	68.83928571	103.4423077	18.80886076
Standard Error	4.391127418	9.549071729	30.96463152	2.771917113
Median	26.7	54.8	61.5	5
Mode	#N/A	54.8	63	4.1
Standard Deviation	10.75602157	50.52893809	157.8892604	42.67312155
Sample Variance	115.692	2553.173585	24929.01854	1820.995303
Kurtosis	-0.774553318	1.04176733	18.73737092	16.39428795
Skewness	0.101108688	1.255455538	4.122241531	4.070285773
Range	29.3	191.9	804.6	239.4
Minimum	12.4	13	19.3	0.7
Maximum	41.7	204.9	823.9	240.1
Sum	158.4	1927.5	2689.5	4457.7
Count	6	28	26	237

	15TH STG BLADE	15TH STG DISK	15TH STG SPACER	15TH STG STATOR
Mean	27.92307692	109.7060606	98.84285714	16.27305936
Standard Error	4.299868123	23.53430279	36.16987786	2.514682498
Median	22	89.1	28.1	5
Mode	#N/A	#N/A	33.1	3.7
Standard Deviation	15.503395	135.1942767	191.3930035	37.21390259
Sample Variance	240.3552564	18277.49246	36631.2818	1384.874546
Kurtosis	0.261708206	4.213833521	11.95094011	18.79293906
Skewness	1.123738487	2.0422223	3.34838149	4.354069107
Range	48.9	530.6	893.1	243.5
Minimum	12.2	6.2	4.1	0.7
Maximum	61.1	536.8	897.2	244.2
Sum	363	3620.3	2767.6	3563.8
Count	13	33	28	219

	16TH STG BLADE	16TH STG DISK
Mean	161.9470588	107.8633333
Standard Error	75.27884395	15.6338731
Median	23.3	115.15
Mode	32.8	155.1
Standard Deviation	310.382625	85.63024958
Sample Variance	96337.3739	7332.539644
Kurtosis	1.685191761	-0.436977678
Skewness	1.865072841	0.528256004
Range	833.8	294.9
Minimum	7.9	5.9
Maximum	841.7	300.8
Sum	2753.1	3235.9
Count	17	30

	9TH STG AIRSEAL	BUSHING	CASE,REAR COMP	HUB REAR
Mean	66.05576923	37.94285714	109.8818182	138.508
Standard Error	9.410074675	8.955986483	26.89021744	51.8147884
Median	46.55	31.3	86.05	42.4
Mode	#N/A	31.3	28	#N/A
Standard Deviation	67.85701349	41.04148598	126.1262996	259.073942
Sample Variance	4604.57428	1684.403571	15907.84346	67119.30743
Kurtosis	17.7342425	20.53690404	5.312173348	14.02359702
Skewness	3.498050191	4.508306735	2.189882459	3.494455173
Range	434.9	195.1	520.7	1234.7
Minimum	6.1	21.1	3	0.9
Maximum	441	216.2	523.7	1235.6
Sum	3434.9	796.8	2417.4	3462.7
Count	52	21	22	25

	HUB-FRONT	NUT #4 BRG IN	NUT COMP	SLEEVE-COMPR DRIVE
Mean	64.2	124.6944444	104.0285714	177.0615385
Standard Error	10.74841687	43.83208712	20.20483815	69.01531188
Median	26.65	79.75	13	57.2
Mode	18	#N/A	13	#N/A
Standard Deviation	98.51086785	185.9637962	141.4338671	248.8382458
Sample Variance	9704.391084	34582.5335	20003.53875	61920.47256
Kurtosis	10.69570318	12.95078469	0.54862395	3.455012965
Skewness	3.029722718	3.38618578	1.300846946	1.873622018
Range	575.6	820.4	530.2	839
Minimum	1.1	0.7	7.8	1.2
Maximum	576.7	821.1	538	840.2
Sum	5392.8	2244.5	5097.4	2301.8
Count	84	18	49	13

	SUPPORT	TIERODS- REAR
Mean	50.93571429	228.0843478
Standard Error	9.563245846	35.07807005
Median	38.95	73.1
Mode	#N/A	223.9
Standard Deviation	35.78238946	376.1703934
Sample Variance	1280.379396	141504.1648
Kurtosis	-1.187311213	4.885455016
Skewness	0.557768636	2.448298247
Range	101.6	1604.5
Minimum	7.1	0.9
Maximum	108.7	1605.4
Sum	713.1	26229.7
Count	14	115

As discussed in Chapter III, the four reparables used in the simulation model were defined as the blade, disk, spacer, and stator. The repair times for each were defined by the aggregated data across all stages for each of the four parts, taken from Table 31. For example, the repair time for the blade used in the model is defined by the aggregated data of the 10^{th}, 11^{th}, 12^{th}, 13^{th}, 14^{th}, 15^{th}, and 16^{th} stage blades.

End-Item Production

Quarterly production plans in the simulation model are drawn from a triangular distribution with parameters varying according to the level of demand variability employed. The parameters for levels 2 and 3 of the demand variability factor, as well as the distribution itself, were selected after an analysis of nine quarters of historical end-item production. The raw data is provided as Table 32 and summarized in Table 33, while a histogram of the data follows as Figure 29.

Table 32: Historical End-Item Production for High Speed Compressor By Production Number (PDN)

PDN	FYQ	IND-S	IND-M
15666A	962	4	43
15666A	963	0	26
15666A	964	0	40
15666A	971	0	20
15666A	972	0	32
15666A	973	0	17
15666A	974	0	15
15666A	981	0	11
15666A	982	0	39
15666C	962	0	17
15666C	963	0	11
15666C	964	0	24
15666C	971	0	7
15666C	972	0	14
15666C	973	0	25
15666C	974	0	31
15666C	981	0	33
15666C	982	0	8
15669A	962	2	16
15669A	963	0	7
15669A	964	0	10
15669A	971	0	12
15669A	972	0	25
15669A	973	0	14
15669A	974	0	23
15669A	981	0	17
15669A	982	0	31

NOTES:

IND-S = Inducted – Supply Generated

IND-M= Inducted – Maintenance Generated

Table 33: Historical End-Item Production for High Speed Compressor (All PDNs)

FYQ	TOTAL INDUCTED
962	82
963	44
964	74
971	39
972	71
973	56
974	69
981	61
982	78
AVG =	63.77778

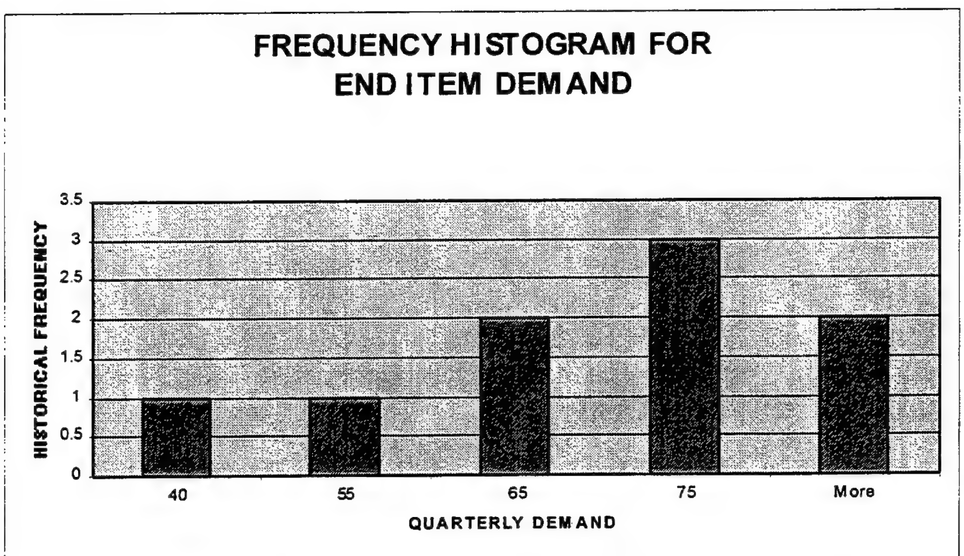


Figure 29: Histogram of Historical Quarterly Production for High Speed Compressor

It is important to note that the parameters for levels 2 and 3 of the demand variability factor were selected to represent the most common and the full range of expected values, respectively. The triangular distribution parameters for level 2, representing the most common values, were 50, 66, and 75. The range covered by level 2, then, is the full range of historical data *excluding the two most extreme points on either end.* Conversely, the range for level 3 of 40 to 82 encompasses the full range of values experienced in the analysis period, *including all extremes.*

Consumable Parts

The eight consumable parts used in the model, like the reparable parts, were defined by the aggregated demand statistics of actual consumable parts. A summary of the demand data for each part is provided in Table 34. The parts were first categorized according to the frequency and size of typical demands. The categories were selected after an analysis of the demand history of all consumable parts associated with the high speed compressor, and capture approximately 93% of the demand patterns identified in the data.

Table 34: Summary of Demand Data for High Speed Compressor Consumable Parts

NSN	# HITS	MEAN HIT	TOTAL
3005	28	294.89	8257
3007	16	259.44	4151
6880	29	308.41	8944
6319	13	406.23	5281
2084	39	10.26	400
5968	30	329.37	9881
6001	37	371.62	13750
6002	6	485.67	2914
6008	37	257.78	9538
8629	8	1.63	13
1254	22	30.23	665
6580	11	510.09	5611
6751	14	437.21	6121
9633	8	24.38	195
8601	7	47.29	331
8602	14	70.79	991
8626	7	2.14	15
8630	4	1.75	7
8631	4	1.50	6
8656	3	1.67	5
8658	3	1.67	5
0084	6	6.83	41
0086	14	1.64	23
0087	13	1.46	19
0088	15	1.60	24
0092	7	1.43	10
6796	20	4.55	91
4001	23	22.57	519
8026	46	57.04	2624
3921	26	1.73	45
0751	5	2.60	13
7267	9	1.44	13
7273	14	3.00	42
4314	1	2.00	2
7322	26	17.42	453
5635	61	26.85	1638
6818	21	17.86	375
6820	8	71.38	571
5358	21	24.24	509
2716	12	89.25	1071
2370	7	5.86	41
2371	17	4.88	83
3012	19	3.47	66

The histograms in Figures 30 and 31 were created using the summary data in Table 34, and were used in the assignment of the consumable parts into five categories. All parts in each category were then used to develop descriptive data for the consumable parts used in the model, such as unit cost, replacement percentage, units per assembly, etc.

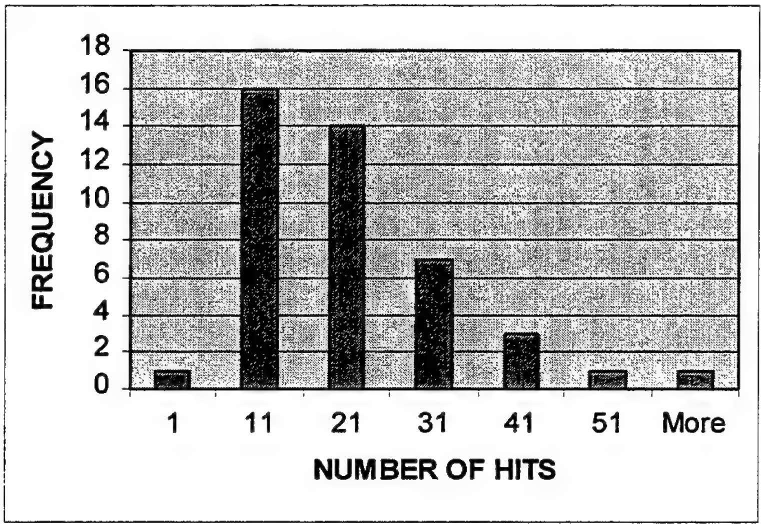


Figure 30: Histogram of Number of Demands by Part

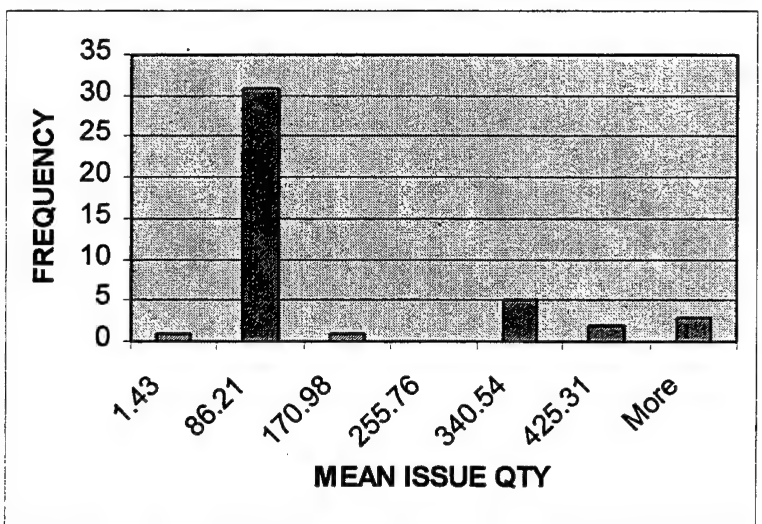


Figure 31: Histogram of Mean Issue Quantity by Part

Table 35 summarizes the five categories by mean issue quantity and demand frequency, and identifies the number of actual consumable parts falling into and the number of model parts derived from each category.

Table 35: Categories of Consumable Parts
Used to Define Model Parts

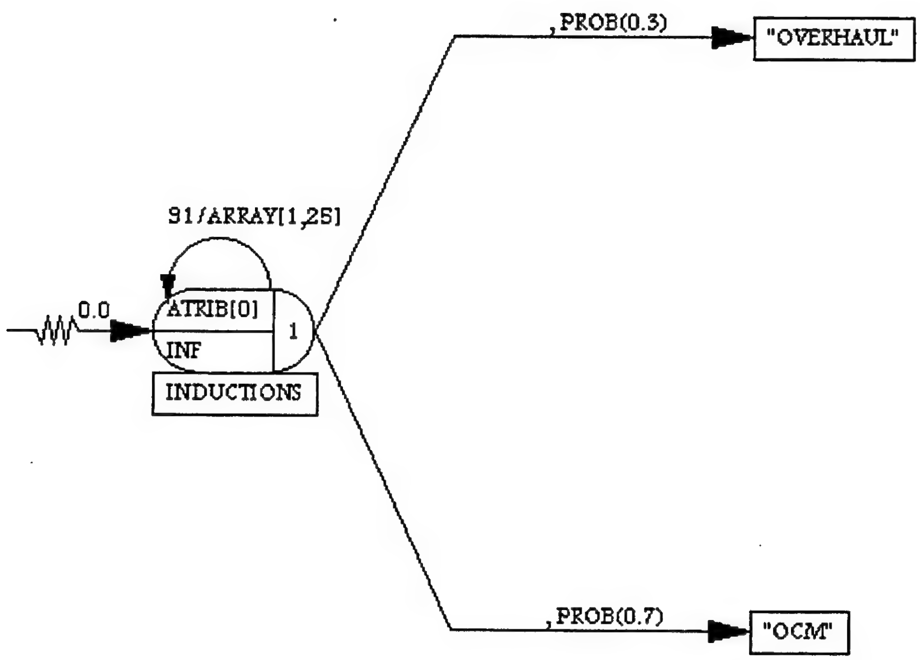
CATEGORY	# HITS	MEAN HIT	FREQUENCY	# PARTS IN MODEL
1	1 TO 21	< 10	19	4
2	1 TO 21	10 TO 86	6	1
3	1 TO 21	256 TO 510	5	1
4	22 TO 41	< 86	5	1
5	22 TO 41	256 TO 510	5	1
TOTALS			40	8

NOTE:
43 PARTS CONSIDERED
40 USED IN CATEGORIES
93% COVERAGE

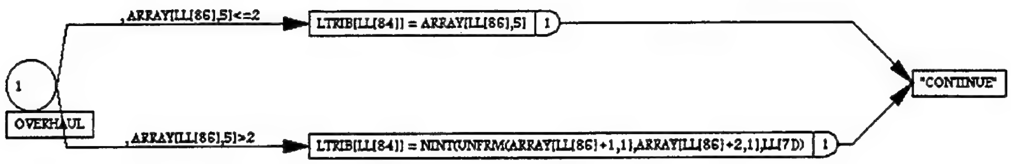
Appendix B: Simulation Model

The Visual SLAM models below show and explain the major processes associated with each model only. For a complete model depiction, refer to the source code that follows each model.

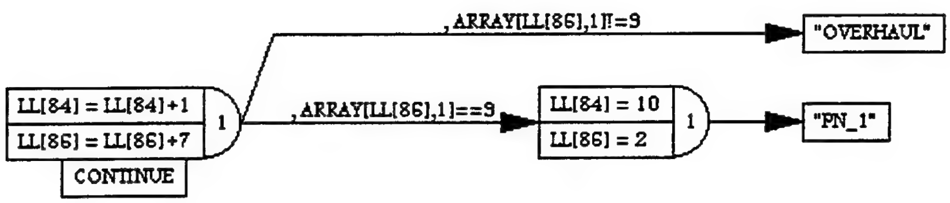
MODEL 1: Visual SLAM Model Components



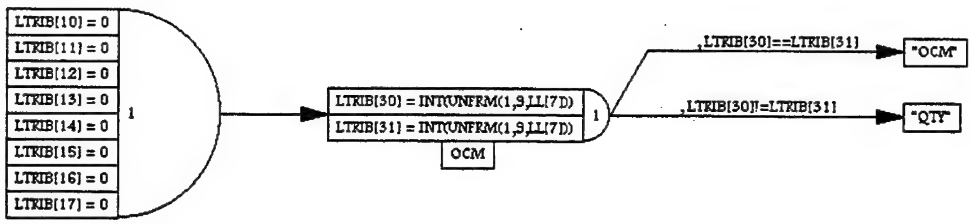
End-item demands are created at a uniform rate according to the current quarterly plan stored in ARRAY[1,25]. Each demand is then routed as either an overhaul or an On-Condition Maintenance (OCM) activity. Thirty percent of repairs are classified as overhauls, and seventy percent as OCM.



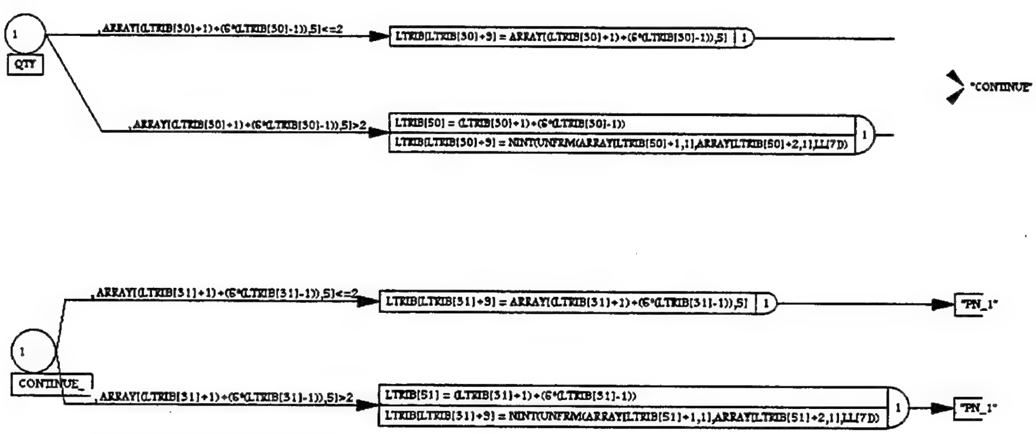
Repairs routed as overhauls are then assigned a repair profile. This involves selecting the number of each part to be replaced in the overhaul process, which is selected from a uniform distribution that is particular to each part.



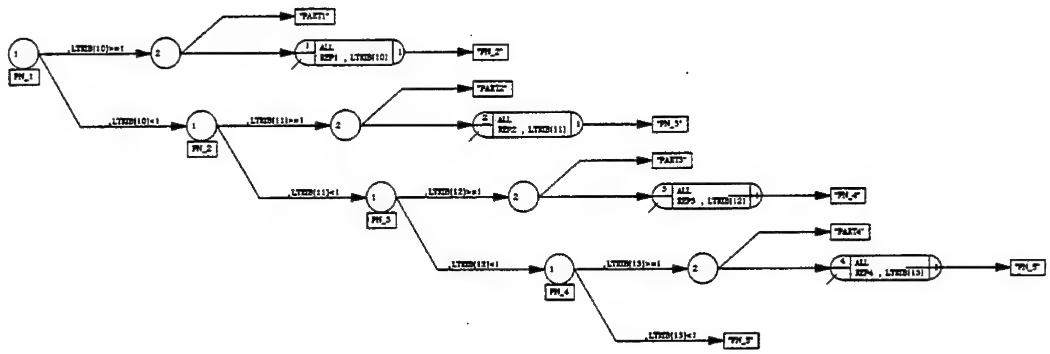
Row and column pointers are incremented, and the repair profile process is repeated for each of the eight level 1 items. When the ninth part is reached, pointers are reset and the repair goes to the material queue for Part 1.



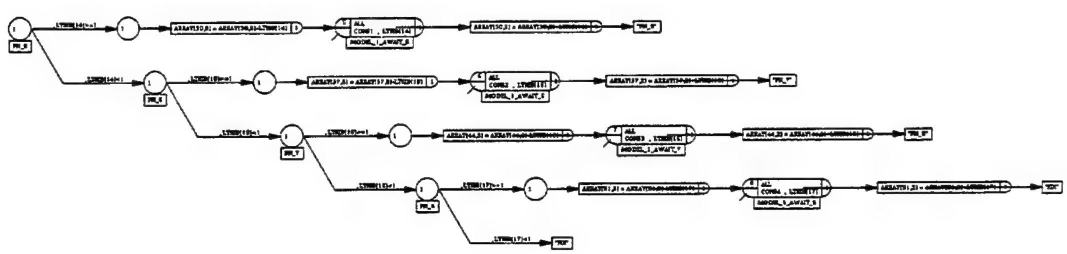
Repairs routed as OCM are assigned a repair profile. The quantity of each item to be replaced is initially set at zero. Two random parts are then selected for replacement, and if they are not the same part are routed to the quantity assignment sub-process. If they are the same part, two new parts are selected.



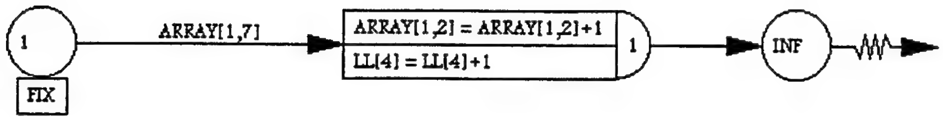
A similar process to the overhaul quantity assignment is performed, where each of the two parts assigned to be replaced is now assigned a quantity to be replaced from a uniform distribution. The repair is then routed to the material queue for Part 1.



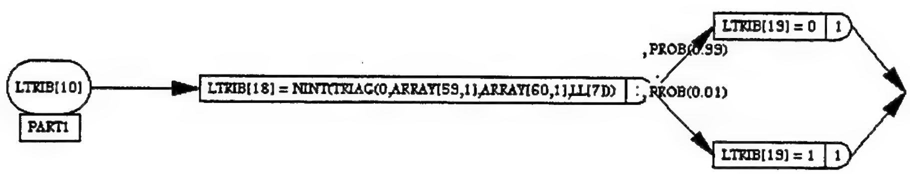
A cascading set of material queues has been developed to preclude excessive waits at a single queue. Using this approach, each repair waits only for those items that it requires. For the above process, each time a level 1 reparable is used, a backshop repair is initiated to replace the item used.



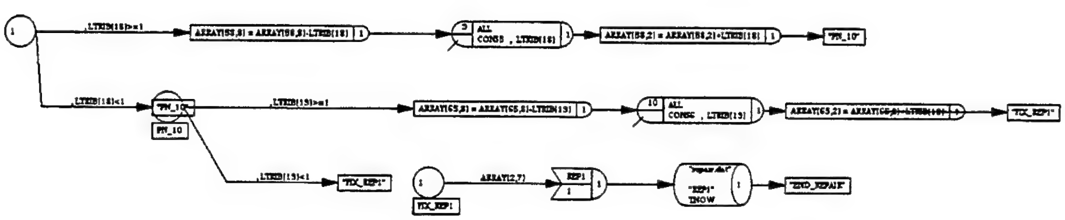
The same process is followed for the level 1 consumable items, the only difference being that the on-hand quantity is adjusted to reflect the demand. All repairs, once they have the materials needed, are next routed to the "fix" process to complete the front shop repair.



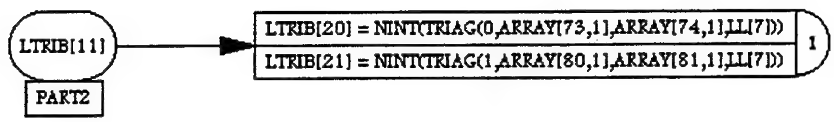
Repair is accomplished according to a deterministic repair time. The current quarter's production level is updated before the repair exits the system.



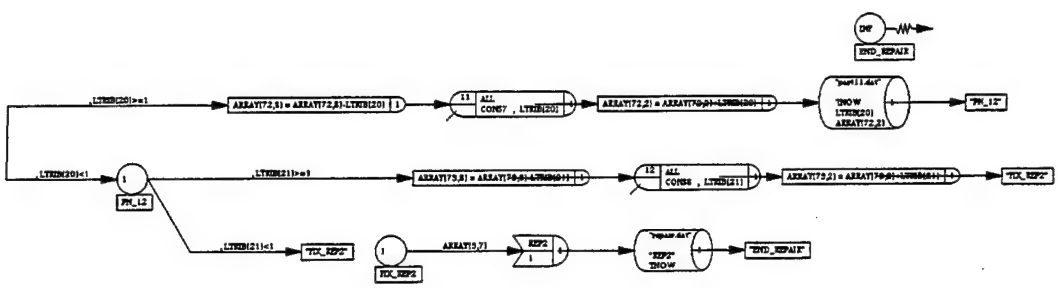
The backshop repair process for Part 1 begins with the assignment of quantity of Part 10 to be used in the repair. Note that the probability of one of Part 10 being used is 0.01. Part 10 is the anomaly built into the system in an attempt to include at least one part with extremely low demand. Such parts generally cause inventory problems.

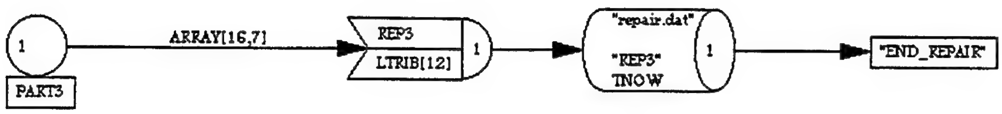


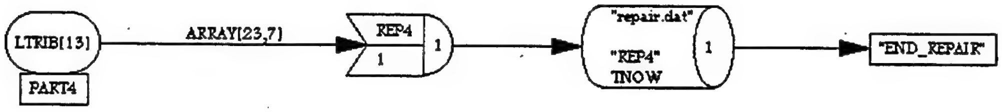
A cascading approach identical to the front shop is used to claim consumables for repair. The on-hand balances are updated accordingly, and when all necessary parts are available, repair is accomplished. Following repair, the repaired item is returned to stock for front shop repairs.



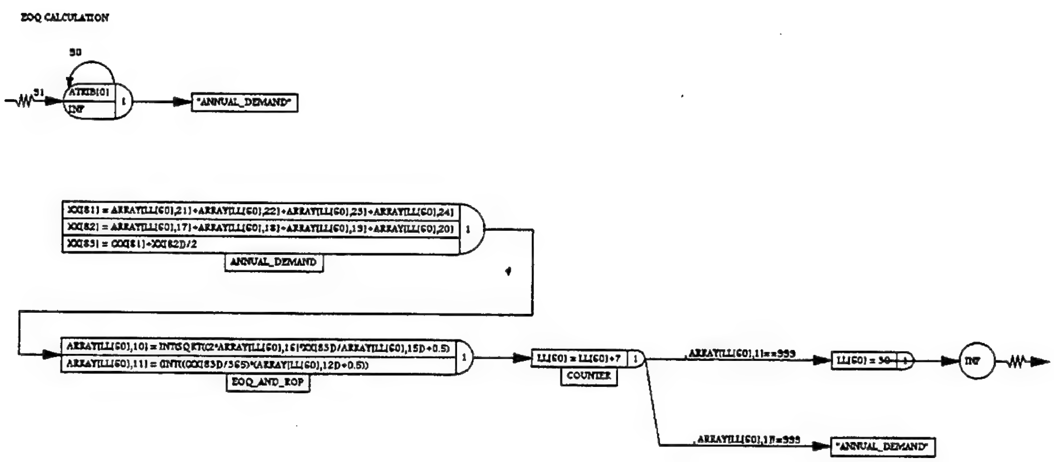
For Part 2, a similar process is followed whereby the quantity of each consumable needed for the repair is assigned according to its distribution. The repair then moves to the same cascading queue process used previously. Again, the item is repaired and returned to stock.



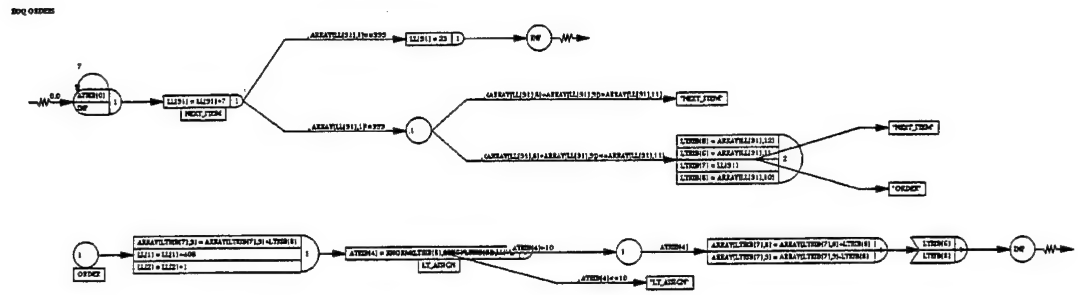




The repair process for Parts 3 and 4 is considerably simpler from a parts perspective, as no consumable parts are required. These represent parts like blades that require primarily machining processes and indirect material.

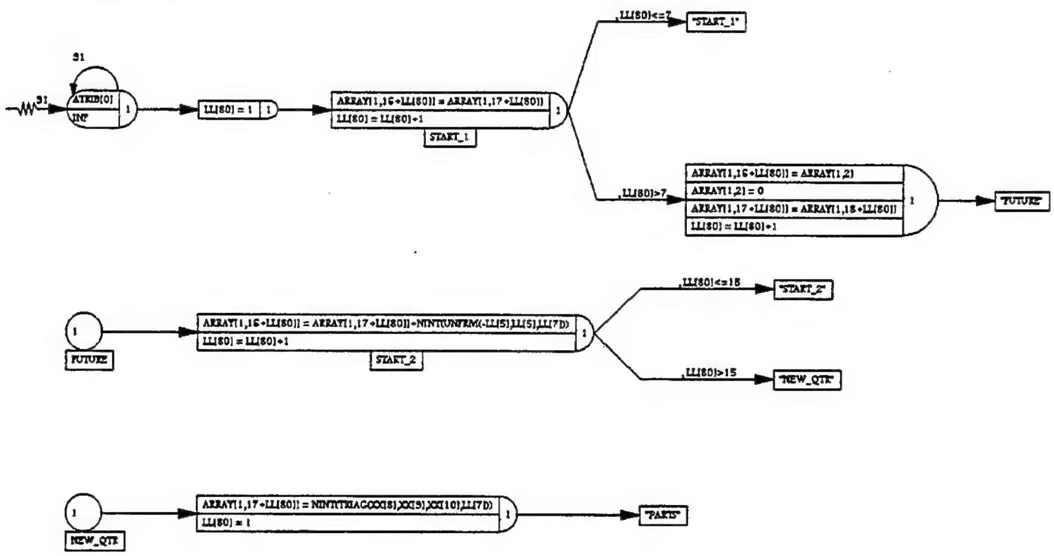


On a quarterly basis, the EOQ and Reorder Point (ROP) are recalculated using the most recent 8 quarters of demand data for each item.



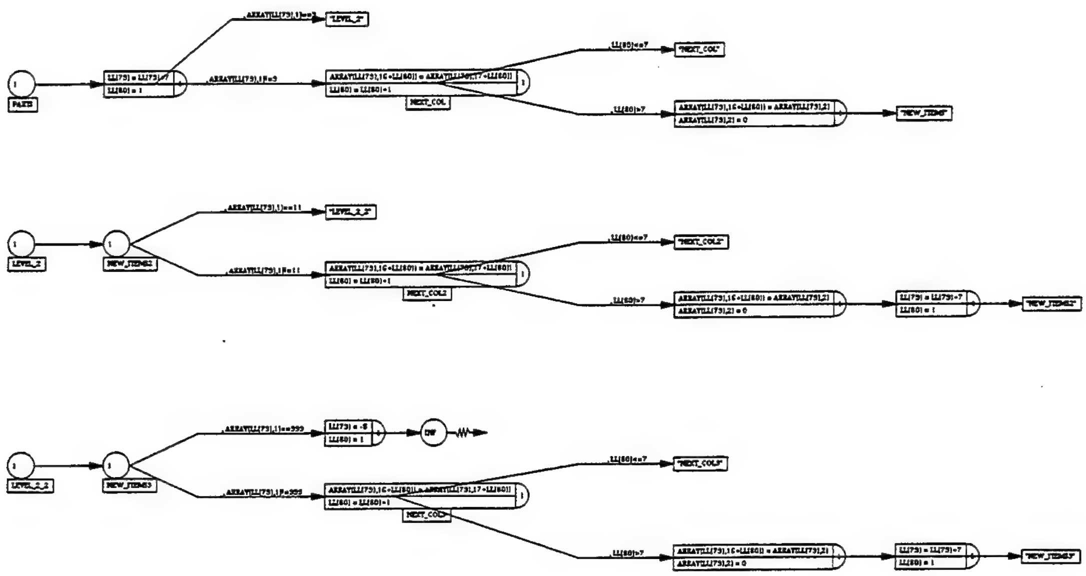
Orders are placed weekly. For each part, the on-hand plus backordered quantity is compared with the ROP. If greater, no action is taken. If below the ROP, an order is initiated. Part number, row reference, lead time, and order quantity are saved as attributes before a copy of the entity is sent to the order sub-process for action. The EOQ of that entity is then ordered, and a lead time is selected from a truncated normal distribution with a mean particular to each item and a standard deviation set according to the factor-level being used. Upon receipt of the item, on-hand and backordered quantities are adjusted accordingly.

PRODUCTION AND INVENTORY PLAN



On a quarterly basis, the end-item production is updated. Past demand is shifted to the left in the array for quarters –8 to –2. The current production for the quarter is then moved to the past demand array as quarter –1. The current quarter through quarter 7 then become the previous values of quarters 1 through 8, adjusted by the demand uncertainty factor according to the level being employed. The forecast for quarter 8 is drawn from a triangular distribution with the parameters determined by the level of demand variability being employed.

Following the update of the end-item production history and forecast, the historical demand of each part is shifted and the current quarter's usage is set as the most current historical quarter (-1).



MODEL 1: Network Source Code

```
RESOURCE,9,CONS5,72,{9};
RESOURCE,10,CONS6,22,{10};
RESOURCE,11,CONS7,425,{11};
RESOURCE,12,CONS8,410,{12};
RESOURCE,1,REP1,15,{1};
RESOURCE,2,REP2,250,{2};
RESOURCE,3,REP3,500,{3};
RESOURCE,4,REP4,15,{4};
RESOURCE,5,CONS1,40,{5};
RESOURCE,6,CONS2,260,{6};
RESOURCE,7,CONS3,5000,{7};
RESOURCE,8,CONS4,6800,{8};
;BACKSHOP REPAIR PROCESSES
;MODULE REPAIR PROCESS: FRONT SHOP
PART1: GOON,LTRIB[10];
ACTIVITY;
ASSIGN,{{LTRIB[18],NINT(TRIAG(0,ARRAY[59,1],ARRAY[60,1],LL[7]))}},1;
ACTIVITY,,,PROB(0.99);
ACTIVITY,,,PROB(0.01),"THESIS1_ASSIGN_1";
ASSIGN,{{LTRIB[19],0}},1;
ACTIVITY;
THESIS1_GOON_1: GOON,1;
ACTIVITY,,,LTRIB[18]>=1;
ACTIVITY,,,LTRIB[18]<1,"PN_10";
ASSIGN,{{ARRAY[58,8],ARRAY[58,8]-LTRIB[18]}},1;
ACTIVITY;
MODEL_1_AWAIT_1: AWAIT,9,{{CONS5,LTRIB[18]}},ALL,,NONE,1;
ACTIVITY;
ASSIGN,{{ARRAY[58,2],ARRAY[58,2]+LTRIB[18]}},1;
ACTIVITY,,,,"PN_10";
PN_10: GOON,1;
ACTIVITY,,,LTRIB[19]>=1;
ACTIVITY,,,LTRIB[19]<1,"FIX_REP1";
ASSIGN,{{ARRAY[65,8],ARRAY[65,8]-LTRIB[19]}},1;
ACTIVITY;
MODEL_1_AWAIT_2: AWAIT,10,{{CONS6,LTRIB[19]}},ALL,,NONE,1;
ACTIVITY;
ASSIGN,{{ARRAY[65,2],ARRAY[65,2]+LTRIB[19]}},1;
ACTIVITY,,,,"FIX_REP1";
THESIS1_ASSIGN_1: ASSIGN,{{LTRIB[19],1}},1;
ACTIVITY,,,,"THESIS1_GOON_1";
INDUCTIONS: CREATE,91/ARRAY[1,25],0.0,ATRIB[0],INF,1;
ACTIVITY,,,PROB(0.3);
ACTIVITY,,,PROB(0.7),"MODEL_1_ASSIGN_3";
OVERHAUL: GOON,1;
ACTIVITY,,,ARRAY[LL[86],5]<=2;
```

```
ACTIVITY,,,ARRAY[LL[86],5]>2,"MODEL_1_ASSIGN_2";
ASSIGN,{{LTRIB[LL[84]],ARRAY[LL[86],5]}},1;
ACTIVITY;
MODEL_1_ASSIGN_1: ASSIGN,{{LL[84],LL[84]+1},{LL[86],LL[86]+7}},1;
ACTIVITY,,,ARRAY[LL[86],1]!=9,"OVERHAUL";
ACTIVITY,,,ARRAY[LL[86],1]==9;
ASSIGN,{{LL[84],10},{LL[86],2}},1;
ACTIVITY,,,,"PN_1";
MODEL_1_ASSIGN_2: ASSIGN,{{LTRIB[LL[84]],NINT(UNFRM(ARRAY[LL[86]+1,1],ARRAY[LL[86]+2,1],LL[7]))}},1;
ACTIVITY,,,,"MODEL_1_ASSIGN_1";
MODEL_1_ASSIGN_3: ASSIGN,{{LTRIB[10],0},{LTRIB[11],0},{LTRIB[12],0},{LTRIB[13],0},{LTRIB[14],0},{LTRIB[15],0},{LTRIB[16],0},{LTRIB[17],0}},1;
ACTIVITY;
OCM: ASSIGN,{{LTRIB[30],INT(UNFRM(1,9,LL[7]))},{LTRIB[31],INT(UNFRM(1,9,LL[7]))}},1;
ACTIVITY,,,LTRIB[30]==LTRIB[31],"OCM";
ACTIVITY,,,LTRIB[30]!=LTRIB[31],"QTY";
FIX_REP1: GOON,1;
ACTIVITY,,ARRAY[2,7];
ALTER,REP1,1,1;
ACTIVITY;
WRITE,"repair.dat",NO,,{"REP1",TNOW},1;
ACTIVITY,,,,"END_REPAIR";
END_REPAIR: TERMINATE,INF;
PART2: GOON,LTRIB[11];
ACTIVITY;
ASSIGN,{{LTRIB[20],NINT(TRIAG(0,ARRAY[73,1],ARRAY[74,1],LL[7]))},{LTRIB[21],NINT(TRIAG(1,ARRAY[80,1],ARRAY[81,1],LL[7]))}},1;
ACTIVITY,,,LTRIB[20]>=1;
ACTIVITY,,,LTRIB[20]<1,"PN_12";
ASSIGN,{{ARRAY[72,8],ARRAY[72,8]-LTRIB[20]}},1;
ACTIVITY;
MODEL_1_AWAIT_3: AWAIT,11,{{CONS7,LTRIB[20]}},ALL,,NONE,1;
ACTIVITY;
ASSIGN,{{ARRAY[72,2],ARRAY[72,2]+LTRIB[20]}},1;
ACTIVITY;
WRITE,"part11.dat",NO,,{TNOW,LTRIB[20],ARRAY[72,2]},1;
ACTIVITY,,,,"PN_12";
PN_12: GOON,1;
ACTIVITY,,,LTRIB[21]>=1;
ACTIVITY,,,LTRIB[21]<1,"FIX_REP2";
ASSIGN,{{ARRAY[79,8],ARRAY[79,8]-LTRIB[21]}},1;
ACTIVITY;
MODEL_1_AWAIT_4: AWAIT,12,{{CONS8,LTRIB[21]}},ALL,,NONE,1;
ACTIVITY;
```

```
 89 ASSIGN,{{ARRAY[79,2],ARRAY[79,2]+LTRIB[21]}},1;
 90 ACTIVITY,,,,"FIX_REP2";
 91 QTY: GOON,1;
 92 ACTIVITY,,,ARRAY[(LTRIB[30]+1)+(6*(LTRIB[30]-1)),5]<=2;
 93 ACTIVITY,,,ARRAY[(LTRIB[30]+1)+(6*(LTRIB[30]-1)),5]>2,"MODEL_1_ASSIGN_5";
 94 ASSIGN,{{LTRIB[LTRIB[30]+9],ARRAY[(LTRIB[30]+1)+(6*(LTRIB[30]-1)),5]}},1;
 95 ACTIVITY;
 96 MODEL_1_GOON_1: GOON,1;
 97 ACTIVITY,,,ARRAY[(LTRIB[31]+1)+(6*(LTRIB[31]-1)),5]<=2;
 98 ACTIVITY,,,ARRAY[(LTRIB[31]+1)+(6*(LTRIB[31]-1)),5]>2,"MODEL_1_ASSIGN_4";
 99 ASSIGN,{{LTRIB[LTRIB[31]+9],ARRAY[(LTRIB[31]+1)+(6*(LTRIB[31]-1)),5]}},1;
100 ACTIVITY,,,,"PN_1";
101 MODEL_1_ASSIGN_4: ASSIGN,{{LTRIB[51],(LTRIB[31]+1)+(6*(LTRIB[31]-
1))},{LTRIB[LTRIB[31]+9],NINT(UNFRM(ARRAY[LTRIB[51]+1,1],ARRAY[LTRIB[51]+2,1
],LL[7]))}},1;
102 ACTIVITY,,,,"PN_1";
103 MODEL_1_ASSIGN_5: ASSIGN,{{LTRIB[50],(LTRIB[30]+1)+(6*(LTRIB[30]-
1))},{LTRIB[LTRIB[30]+9],NINT(UNFRM(ARRAY[LTRIB[50]+1,1],ARRAY[LTRIB[50]+2,1
],LL[7]))}},1;
104 ACTIVITY,,,,"MODEL_1_GOON_1";
105 FIX_REP2: GOON,1;
106 ACTIVITY,,ARRAY[9,7];
107 ALTER,REP2,1,1;
108 ACTIVITY;
109 WRITE,"repair.dat",NO,,{"REP2",TNOW},1;
110 ACTIVITY,,,,"END_REPAIR";
111 PART3: GOON,1;
112 ACTIVITY,,ARRAY[16,7];
113 ALTER,REP3,LTRIB[12],1;
114 ACTIVITY;
115 WRITE,"repair.dat",NO,,{"REP3",TNOW},1;
116 ACTIVITY,,,,"END_REPAIR";
117 PN_1: GOON,1;
118 ACTIVITY,,,LTRIB[10]>=1;
119 ACTIVITY,,,LTRIB[10]<1,"PN_2";
120 GOON,2;
121 ACTIVITY,,,,"PART1";
122 ACTIVITY;
123 AWAIT,1,{{REP1,LTRIB[10]}},ALL,,NONE,1;
124 ACTIVITY,,,,"PN_2";
125 PN_2: GOON,1;
126 ACTIVITY,,,LTRIB[11]>=1;
127 ACTIVITY,,,LTRIB[11]<1,"PN_3";
128 GOON,2;
129 ACTIVITY,,,,"PART2";
130 ACTIVITY;
131 AWAIT,2,{{REP2,LTRIB[11]}},ALL,,NONE,1;
132 ACTIVITY,,,,"PN_3";
133 PN_3: GOON,1;
```

```
ACTIVITY,,,LTRIB[12]>=1;
ACTIVITY,,,LTRIB[12]<1,"PN_4";
GOON,2;
ACTIVITY,,,,"PART3";
ACTIVITY;
AWAIT,3,{{REP3,LTRIB[12]}},ALL,,NONE,1;
ACTIVITY,,,,"PN_4";
PN_4: GOON,1;
ACTIVITY,,,LTRIB[13]>=1;
ACTIVITY,,,LTRIB[13]<1,"PN_5";
GOON,2;
ACTIVITY,,,,"PART4";
ACTIVITY;
AWAIT,4,{{REP4,LTRIB[13]}},ALL,,NONE,1;
ACTIVITY,,,,"PN_5";
PART4: GOON,LTRIB[13];
ACTIVITY,,ARRAY[23,7];
ALTER,REP4,1,1;
ACTIVITY;
WRITE,"repair.dat",NO,,{"REP4",TNOW},1;
ACTIVITY,,,,"END_REPAIR";
FIX: GOON,1;
ACTIVITY,,ARRAY[1,7],,,,"END-ITEM FIX";
ASSIGN,{{ARRAY[1,2],ARRAY[1,2]+1},{LL[4],LL[4]+1}},1;
ACTIVITY;
TERMINATE,INF;
PN_5: GOON,1;
ACTIVITY,,,LTRIB[14]>=1;
ACTIVITY,,,LTRIB[14]<1,"PN_6";
GOON,1;
ACTIVITY;
ASSIGN,{{ARRAY[30,8],ARRAY[30,8]-LTRIB[14]}},1;
ACTIVITY;
MODEL_1_AWAIT_5: AWAIT,5,{{CONS1,LTRIB[14]}},ALL,,NONE,1;
ACTIVITY;
ASSIGN,{{ARRAY[30,2],ARRAY[30,2]+LTRIB[14]}},1;
ACTIVITY,,,,"PN_6";
PN_6: GOON,1;
ACTIVITY,,,LTRIB[15]>=1;
ACTIVITY,,,LTRIB[15]<1,"PN_7";
GOON,1;
ACTIVITY;
ASSIGN,{{ARRAY[37,8],ARRAY[37,8]-LTRIB[15]}},1;
ACTIVITY;
MODEL_1_AWAIT_6: AWAIT,6,{{CONS2,LTRIB[15]}},ALL,,NONE,1;
ACTIVITY;
ASSIGN,{{ARRAY[37,2],ARRAY[37,2]+LTRIB[15]}},1;
ACTIVITY,,,,"PN_7";
PN_7: GOON,1;
```

```
ACTIVITY,,,LTRIB[16]>=1;
ACTIVITY,,,LTRIB[16]<1,"PN_8";
GOON,1;
ACTIVITY;
ASSIGN,{{ARRAY[44,8],ARRAY[44,8]-LTRIB[16]}},1;
ACTIVITY;
MODEL_1_AWAIT_7: AWAIT,7,{{CONS3,LTRIB[16]}},ALL,,NONE,1;
ACTIVITY;
ASSIGN,{{ARRAY[44,2],ARRAY[44,2]+LTRIB[16]}},1;
ACTIVITY,,,,"PN_8";
PN_8: GOON,1;
ACTIVITY,,,LTRIB[17]>=1;
ACTIVITY,,,LTRIB[17]<1,"FIX";
GOON,1;
ACTIVITY;
ASSIGN,{{ARRAY[51,8],ARRAY[51,8]-LTRIB[17]}},1;
ACTIVITY;
MODEL_1_AWAIT_8: AWAIT,8,{{CONS4,LTRIB[17]}},ALL,,NONE,1;
ACTIVITY;
ASSIGN,{{ARRAY[51,2],ARRAY[51,2]+LTRIB[17]}},1;
ACTIVITY,,,,"FIX";
;EOQ CALCULATION
CREATE,90,91,ATRIB[0],INF,1;
ACTIVITY,,,,"ANNUAL_DEMAND";
ANNUAL_DEMAND: ASSIGN,{{XX[81],ARRAY[LL[60],21]+ARRAY[LL[60],22]+ARRAY[LL[60],23]+ARRAY[LL[60],24]},{XX[82],ARRAY[LL[60],17]+ARRAY[LL[60],18]+ARRAY[LL[60],19]+ARRAY[LL[60],20]},{XX[83],(XX[81]+XX[82])/2}},1;
ACTIVITY;
EOQ_AND_ROP: ASSIGN,{{ARRAY[LL[60],10],INT(SQRT((2*ARRAY[LL[60],16]*XX[83])/ARRAY[LL[60],15])+0.5)},{ARRAY[LL[60],11],(INT(((XX[83])/365)*(ARRAY[LL[60],12])+0.5))}},1;
ACTIVITY;
WRITE,"eoq_calc.dat",NO,,{TNOW,ARRAY[LL[60],1],XX[83],ARRAY[LL[60],10],ARRAY[LL[60],11]},1;
ACTIVITY;
COUNTER: ASSIGN,{{LL[60],LL[60]+7}},1;
ACTIVITY,,,ARRAY[LL[60],1]==999;
ACTIVITY,,,ARRAY[LL[60],1]!=999,"ANNUAL_DEMAND";
ASSIGN,{{LL[60],30}},1;
ACTIVITY;
TERMINATE,INF;
;EOQ ORDERS
CREATE,7,0.0,ATRIB[0],INF,1;
ACTIVITY;
NEXT_ITEM: ASSIGN,{{LL[91],LL[91]+7}},1;
ACTIVITY,,,ARRAY[LL[91],1]==999;
ACTIVITY,,,ARRAY[LL[91],1]!=999,"THESIS1_WRITE_1";
```

```
ASSIGN,{{LL[91],23}},1;
ACTIVITY;
TERMINATE,INF;
THESIS1_WRITE_1: WRITE,"order.dat",NO,,{ARRAY[LL[91],1],ARRAY[LL[91],8],ARRAY[LL[91],9],ARRAY[LL[91],11]},1;
ACTIVITY;
THESIS1_GOON_4: GOON,1;
ACTIVITY,,,(ARRAY[LL[91],8]+ARRAY[LL[91],9])>ARRAY[LL[91],11],"NEXT_ITEM";
ACTIVITY,,,(ARRAY[LL[91],8]+ARRAY[LL[91],9])<=ARRAY[LL[91],11];
ASSIGN,{{LTRIB[5],ARRAY[LL[91],12]},{LTRIB[6],ARRAY[LL[91],1]},{LTRIB[7],LL[91]},{LTRIB[8],ARRAY[LL[91],10]}},2;
ACTIVITY,,,,"NEXT_ITEM";
ACTIVITY,,,,"ORDER";
ORDER: GOON,1;
ACTIVITY;
WRITE,"eoq_order.dat",NO,,{TNOW,LTRIB[6],LTRIB[8],ARRAY[LTRIB[7],8],ARRAY[LTRIB[7],11] },1;
ACTIVITY;
ASSIGN,{{ATRIB[3],TNOW}},1;
ACTIVITY;
ASSIGN,{{ARRAY[LTRIB[7],9],ARRAY[LTRIB[7],9]+LTRIB[8]},{LL[1],LL[1]+405},{LL[2],LL[2]+1}},1;
ACTIVITY;
LT_ASSIGN: ASSIGN,{{ATRIB[4],RNORM(LTRIB[5],(XX[6]*LTRIB[5]),LL[7])}},1;
ACTIVITY,,,ATRIB[4]>10;
ACTIVITY,,,ATRIB[4]<=10,"LT_ASSIGN";
GOON,1;
ACTIVITY,,ATRIB[4];
WRITE,"bill.dat",NO,,{LTRIB[6],LTRIB[5],LTRIB[8],TNOW},1;
ACTIVITY;
ASSIGN,{{ARRAY[LTRIB[7],8],ARRAY[LTRIB[7],8]+LTRIB[8]},{ARRAY[LTRIB[7],9],ARRAY[LTRIB[7],9]-LTRIB[8]}},1;
ACTIVITY;
ALTER,LTRIB[6],LTRIB[8],1;
ACTIVITY;
TERMINATE,INF;
;PRODUCTION AND INVENTORY PLAN
CREATE,91,91,ATRIB[0],INF,1;
ACTIVITY;
WRITE,"prod.dat",NO,,{TNOW,ARRAY[1,2]},1;
ACTIVITY;
ASSIGN,{{LL[80],1}},1;
ACTIVITY;
```

```
263 START_1:
ASSIGN,{{ARRAY[1,16+LL[80]],ARRAY[1,17+LL[80]]},{LL[80],LL[80]+1}},1;
264 ACTIVITY,,,LL[80]<=7,"START_1";
265 ACTIVITY,,,LL[80]>7;
266
ASSIGN,{{ARRAY[1,16+LL[80]],ARRAY[1,2]},{ARRAY[1,2],0},{ARRAY[1,17+LL[80]],AR
RAY[1,18+LL[80]]},{LL[80],LL[80]+1}},1;
267 ACTIVITY,,,,"FUTURE";
268 FUTURE: GOON,1;
269 ACTIVITY;
270 START_2: ASSIGN,{{ARRAY[1,16+LL[80]],ARRAY[1,17+LL[80]]+NINT(UNFRM(-
LL[5],LL[5],LL[7]))},{LL[80],LL[80]+1}},1;
271 ACTIVITY,,,LL[80]<=15,"START_2";
272 ACTIVITY,,,LL[80]>15,"NEW_QTR";
273 NEW_QTR: GOON,1;
274 ACTIVITY;
275
ASSIGN,{{ARRAY[1,17+LL[80]],NINT(TRIAG(XX[8],XX[9],XX[10],LL[7]))},{LL[80],1}},1;
276 ACTIVITY,,,,"PARTS";
277 PARTS: GOON,1;
278 ACTIVITY;
279 NEW_ITEMS: ASSIGN,{{LL[79],LL[79]+7},{LL[80],1}},1;
280 ACTIVITY,,,ARRAY[LL[79],1]==9,"LEVEL_2";
281 ACTIVITY,,,ARRAY[LL[79],1]!=9,"NEXT_COL";
282 NEXT_COL:
ASSIGN,{{ARRAY[LL[79],16+LL[80]],ARRAY[LL[79],17+LL[80]]},{LL[80],LL[80]+1}},1;
283 ACTIVITY,,,LL[80]<=7,"NEXT_COL";
284 ACTIVITY,,,LL[80]>7;
285 ASSIGN,{{ARRAY[LL[79],16+LL[80]],ARRAY[LL[79],2]},{ARRAY[LL[79],2],0}},1;
286 ACTIVITY;
287
WRITE,"parts.dat",NO,,{TNOW,ARRAY[LL[79],1],ARRAY[LL[79],17],ARRAY[LL[79],18],
ARRAY[LL[79],19],ARRAY[LL[79],20],ARRAY[LL[79],21],ARRAY[LL[79],22],ARRAY[LL[
79],23],ARRAY[LL[79],24]},1;
288 ACTIVITY,,,,"NEW_ITEMS";
289 LEVEL_2: GOON,1;
290 ACTIVITY;
291 NEW_ITEMS2: GOON,1;
292 ACTIVITY,,,ARRAY[LL[79],1]==11,"LEVEL_2_2";
293 ACTIVITY,,,ARRAY[LL[79],1]!=11;
294 NEXT_COL2:
ASSIGN,{{ARRAY[LL[79],16+LL[80]],ARRAY[LL[79],17+LL[80]]},{LL[80],LL[80]+1}},1;
295 ACTIVITY,,,LL[80]<=7,"NEXT_COL2";
296 ACTIVITY,,,LL[80]>7;
297 ASSIGN,{{ARRAY[LL[79],16+LL[80]],ARRAY[LL[79],2]},{ARRAY[LL[79],2],0}},1;
298 ACTIVITY;
299
WRITE,"parts.dat",NO,,{TNOW,ARRAY[LL[79],1],ARRAY[LL[79],17],ARRAY[LL[79],18],
```

```
ARRAY[LL[79],19],ARRAY[LL[79],20],ARRAY[LL[79],21],ARRAY[LL[79],22],ARRAY[LL[
79],23],ARRAY[LL[79],24]},1;
 300 ACTIVITY;
 301 ASSIGN,{{LL[79],LL[79]+7},{LL[80],1}},1;
 302 ACTIVITY,,,,"NEW_ITEMS2";
 303 LEVEL_2_2: GOON,1;
 304 ACTIVITY;
 305 NEW_ITEMS3: GOON,1;
 306 ACTIVITY,,,ARRAY[LL[79],1]==999;
 307 ACTIVITY,,,ARRAY[LL[79],1]!=999,"NEXT_COL3";
 308 ASSIGN,{{LL[79],-5},{LL[80],1}},1;
 309 ACTIVITY;
 310
WRITE,"prod.dat",NO,,{ARRAY[1,17],ARRAY[1,18],ARRAY[1,19],ARRAY[1,20],ARRAY[
1,21],ARRAY[1,22],ARRAY[1,23],ARRAY[1,24],ARRAY[1,25],ARRAY[1,26],ARRAY[1,2
7],ARRAY[1,28],ARRAY[1,29],ARRAY[1,30],ARRAY[1,31],ARRAY[1,32],ARRAY[1,33]},
1;
 311 ACTIVITY;
 312 TERMINATE,INF;
 313 NEXT_COL3:
ASSIGN,{{ARRAY[LL[79],16+LL[80]],ARRAY[LL[79],17+LL[80]]},{LL[80],LL[80]+1}},1;
 314 ACTIVITY,,,LL[80]<=7,"NEXT_COL3";
 315 ACTIVITY,,,LL[80]>7;
 316 ASSIGN,{{ARRAY[LL[79],16+LL[80]],ARRAY[LL[79],2]},{ARRAY[LL[79],2],0}},1;
 317 ACTIVITY;
 318
WRITE,"parts.dat",NO,,{TNOW,LL[79],LL[80],ARRAY[LL[79],1],ARRAY[LL[79],17],ARR
AY[LL[79],18],ARRAY[LL[79],19],ARRAY[LL[79],20],ARRAY[LL[79],21],ARRAY[LL[79],2
2],ARRAY[LL[79],23],ARRAY[LL[79],24]},1;
 319 ACTIVITY;
 320 ASSIGN,{{LL[79],LL[79]+7},{LL[80],1}},1;
 321 ACTIVITY,,,,"NEW_ITEMS3";
 322 CREATE,7,7,ATRIB[0],INF,1;
 323 ACTIVITY;
 324 NEW: ASSIGN,{{LL[70],1},{LL[51],25},{LL[52],0},{LL[69],LL[69]+7}},1;
 325 ACTIVITY,,,ARRAY[LL[69],1]==9,"CURRENT2";
 326 ACTIVITY,,,ARRAY[LL[69],1]!=9,"NXT_QTR";
 327 NXT_QTR: ASSIGN,{{LL[50],1},{LL[52],0}},1;
 328 ACTIVITY;
 329 FUTR:
ASSIGN,{{ARRAY[LL[69],24+LL[70]],NINT((ARRAY[1,LL[51]+INT(ARRAY[LL[69],12]/90
)]*ARRAY[LL[69],6])/13)},{LL[50],LL[50]+1},{LL[52],LL[52]+ARRAY[LL[69],16+LL[70]]},{L
L[70],LL[70]+1}},1;
 330 ACTIVITY,,,LL[50]<=12,"FUTR";
 331 ACTIVITY,,,LL[50]>12,"LAST_WEEK";
 332 LAST_WEEK: GOON,1;
 333 ACTIVITY,,,LL[52]<ARRAY[1,LL[51]+NINT(ARRAY[LL[69],12]/90)];
```

```
ACTIVITY,,,LL[52]>=ARRAY[1,LL[51]+NINT(ARRAY[LL[69],12]/90)],"TEST_ASSIGN_11";
ASSIGN,{{ARRAY[LL[69],16+LL[70]],ARRAY[1,LL[51]+NINT(ARRAY[LL[69],12]/90)]-LL[52]},{LL[70],LL[70]+1},{LL[51],LL[51]+1}},1;
ACTIVITY;
TEST_GOON_3: GOON,1;
ACTIVITY,,,LL[51]>27,"NEW";
ACTIVITY,,,LL[51]<=27,"NXT_QTR";
TEST_ASSIGN_11: ASSIGN,{{ARRAY[LL[69],16+LL[70]],0},{LL[70],LL[70]+1},{LL[51],LL[51]+1}},1;
ACTIVITY,,,,"TEST_GOON_3";
CURRENT2: GOON,1;
ACTIVITY,,,ARRAY[LL[69],1]==11,"CURRENT3";
ACTIVITY,,,ARRAY[LL[69],1]!=11;
FUTR2: ASSIGN,{{ARRAY[LL[69],24+LL[70]],ARRAY[2,24+LL[70]+INT(ARRAY[LL[69],12]/90)+1]*ARRAY[LL[69],6]},{LL[70],LL[70]+1}},1;
ACTIVITY,,,24+LL[70]+INT(ARRAY[LL[69],12]/90)+1<=63,"FUTR2";
ACTIVITY,,,24+LL[70]+INT(ARRAY[LL[69],12]/90)+1>63;
ASSIGN,{{LL[69],LL[69]+7},{LL[70],1}},1;
ACTIVITY,,,,"CURRENT2";
CURRENT3: GOON,1;
ACTIVITY,,,ARRAY[LL[69],1]==999;
ACTIVITY,,,ARRAY[LL[69],1]!=999,"FUTR3";
ASSIGN,{{LL[50],1},{LL[69],-5},{LL[70],1}},1;
ACTIVITY;
TERMINATE,INF;
FUTR3: ASSIGN,{{ARRAY[LL[69],24+LL[70]],ARRAY[9,24+LL[70]+INT(ARRAY[LL[69],12]/90)+1]*ARRAY[LL[69],6]},{LL[70],LL[70]+1}},1;
ACTIVITY,,,24+LL[70]+INT(ARRAY[LL[69],12]/90)+1<=63,"FUTR3";
ACTIVITY,,,24+LL[70]+INT(ARRAY[LL[69],12]/90)+1>63;
ASSIGN,{{LL[69],LL[69]+7},{LL[70],1}},1;
ACTIVITY,,,,"CURRENT3";
```

MODEL 1: Control Source Code

```
GEN,"Kevin Gaudette","Thesis Test",1 July 1998,35,YES,YES,1;
LIMITS,100,100,,20,60,,5000;
INITIALIZE,0,5110,YES;
MONTR,CLEAR,1460;
INTLC,{{LL[5],5},{XX[6],0.4},{LL[7],21},{XX[8],62.5},{XX[9],63.5},{XX[10],64}};
INTLC,{{LL[44],0}};
INTLC,{{LL[50],1},{LL[51],25},{LL[52],0},{LL[69],-5},{LL[70],1}};
INTLC,{{LL[83],10},{LL[84],10},{LL[85],2},{LL[86],2}};
INTLC,{{LL[60],30},{LL[90],-5},{LL[92],23},{LL[93],-5}};
INTLC,{{LL[1],0},{LL[2],0},{LL[3],0},{LL[4],0},{LL[91],23}};
INTLC,{{LL[79],-5},{LL[80],1}};
INTLC,{{LL[93],-5},{LL[94],1},{LL[95],1}};
INTLC,{{LL[96],-5},{LL[97],1},{LL[98],2},{LL[99],-5},{LL[100],1}};
INTLC,{{LL[81],-5},{LL[82],2}};
ARRAY,1,33,{0,0,0.7,0,0,0,15,0,0,0,0,0,231583,0,0,82,44,74,39,71,56,69,61,78,55,59,
76,73,71,61,72,53};
ARRAY,2,63,{1,0,0.8,0,1,0.3,20,27,0,0,0,20,20,1625,0,0,82,44,74,39,71,56,69,61,2,2,2,
2,2,2,2,2,2,2,2,2,0,1,1,1,1,1,1,1,1,1,1,1,5,1,1,1,1,1,1,1,1,1,1,1,6};
ARRAY,3,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,
0,0};
ARRAY,4,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,
0,0};
ARRAY,5,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,
0,0};
ARRAY,6,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,
0,0};
ARRAY,7,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,
0,0};
ARRAY,8,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,
0,0};
ARRAY,9,63,{2,0,0.8,0,1,0.86,7,12,0,0,0,7,7,16875,0,0,82,44,74,39,71,56,69,61,5,5,5,5,
5,5,5,5,5,5,5,5,7,4,4,4,4,4,4,4,4,4,4,4,0,4,4,4,4,4,4,4,4,4,4,4,4,3};
ARRAY,10,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
ARRAY,11,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
```

```
 26
ARRAY,12,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
 27
ARRAY,13,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
 28
ARRAY,14,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
 29
ARRAY,15,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
 30
ARRAY,16,63,{3,0,1,0,80,22,27,500,0,0,0,27,27,147,0,0,1805,969,1629,859,1563,1233,
1519,1343,132,132,132,132,132,132,132,132,132,132,132,132,132
,93,93,93,93,93,93,93,93,93,93,93,93,94,100,100,100,100
,100,100,100,100,100,100,100 ,100,98};
 31
ARRAY,17,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
 32
ARRAY,18,41,{44,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,
0,0,0};
 33
ARRAY,19,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
 34
ARRAY,20,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
 35
ARRAY,21,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
 36
ARRAY,22,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
 37
ARRAY,23,63,{4,0,1,0,1,0.88,23,29,0,0,0,23,23,9089,0,0,82,44,74,39,71,56,69,61,5,5,5,
5,5,5,5,5,5,5 ,5,5,9,4,4,4,4,4,4,4,4,4,4,4,4,0,4,4,4,4,4,4,4,4,4,4,4,4};
 38
ARRAY,24,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
 39
ARRAY,25,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
 40
ARRAY,26,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
```

41
ARRAY,27,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
42
ARRAY,28,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
43
ARRAY,29,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
44
ARRAY,30,63,{5,0,49,0,2,1.5,0,40,0,221,46,95,95,17,2.89,405,58,31,52,27,50,39,49,43,
6,6,6,6,6,6,6,6,6,6,6,6,11,7,7,7,7,7,7,7,7,7,7,7,7,5,9,9,9,9,9,9,9,9,9,9,9,9,6};
45
ARRAY,31,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
46
ARRAY,32,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
47
ARRAY,33,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
48
ARRAY,34,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
49
ARRAY,35,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
50
ARRAY,36,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
51
ARRAY,37,63,{6,0,250,0,16,5,0,260,0,1182,185,115,115,2,0.34,405,194,104,175,92,16
8,133,163,144,21,21,21,21,21,21,21,21,21,21,21,21,23,23,23,23,23,23,23,23,23,23,23,2
3,23,19,29,29,29,29,29,29,29,29,29,29,29,29,32};
52
ARRAY,38,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
53
ARRAY,39,41,{10,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,
0,0,0};
54
ARRAY,40,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
55
ARRAY,41,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
56
ARRAY,42,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};

```
 57
ARRAY,43,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
 58
ARRAY,44,63,{7,0,1216,0,75,60,0,5000,0,5803,3640,188,188,1,0.17,405,2337,1254,21
09,1111,2093,1596,1966,1738,272,272,272,272,272,272,272,272,272,272,272,272,276,
351,351,351,351,351,351,351,351,351,351,351,351,348,337,337,337,337,337,337,337,
337,337,337,337,337,336};
 59
ARRAY,45,41,{45,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,
0,0,0};
 60
ARRAY,46,41,{75,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,
0,0,0};
 61
ARRAY,47,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
 62
ARRAY,48,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
 63
ARRAY,49,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
 64
ARRAY,50,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
 65
ARRAY,51,63,{8,0,1459,0,80,76,0,6800,0,2666,5052,206,206,6,1.02,405,2960,1588,26
71,1407,2563,2021,2490,2202,345,345,345,345,345,345,345,345,345,345,345,345,344,
444,444,444,444,444,444,444,444,444,444,444,444,448,427,427,427,427,427,427,427,
427,427,427,427,427,424};
 66
ARRAY,52,41,{72,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,
0,0,0};
 67
ARRAY,53,41,{80,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,
0,0,0};
 68
ARRAY,54,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
 69
ARRAY,55,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
 70
ARRAY,56,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
 71
ARRAY,57,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
```

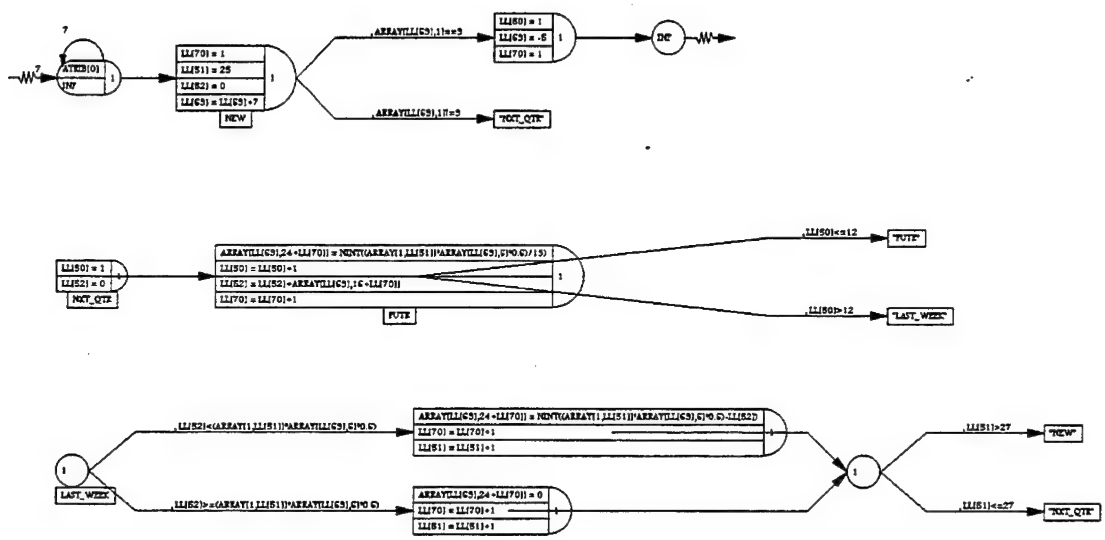
72
ARRAY,58,63,{9,0,73,0,6,1.6,0,72,0,256,20,105,125,5,0.85,405,23,12,21,11,20,15,19,1
7,1,1,1,1,1,1,1,1,1,1,1,1,0,1,1,1,1,1,1,1,1,1,1,1,1,0,1,1,1,1,1,1,1,1,1,1,1,1,0};
73
ARRAY,59,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
74
ARRAY,60,41,{6,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
75
ARRAY,61,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
76
ARRAY,62,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
77
ARRAY,63,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
78
ARRAY,64,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
79
ARRAY,65,63,{10,0,25,0,1,0.01,0,22,0,80,2,142,162,3,0.51,405,1,1,1,1,1,1,1,1,1,1,1,1,1
,1,1,1,1,1,1,1,0,1,1,1,1,1,1,1,1,1,1,1,1,0,1,1,1,1,1,1,1,1,1,1,1,1,0};
80
ARRAY,66,41,{0.53,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,
0,0,0,0};
81
ARRAY,67,41,{1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
82
ARRAY,68,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
83
ARRAY,69,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
84
ARRAY,70,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
85
ARRAY,71,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
86
ARRAY,72,63,{11,0,146,0,16,4.5,0,425,0,345,125,121,128,15,2.55,405,124,66,112,59,1
07,85,104,92,16,16,16,16,16,16,16,16,16,16,16,16,0,16,16,16,16,16,16,16,16,16,16,16,
16,0,16,16,16,16,16,16,16,16,16,16,16,16,0};
87
ARRAY,73,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};

```
 88
ARRAY,74,41,{16,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,
0,0,0};
 89
ARRAY,75,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
 90
ARRAY,76,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
 91
ARRAY,77,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
 92
ARRAY,78,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
 93
ARRAY,79,63,{12,0,122,0,10,3.5,0,410,0,374,211,164,171,16,2.72,405,155,83,140,74,1
34,106,131,115,20,20,20,20,20,20,20,20,20,20,20,0,20,20,20,20,20,20,20,20,20,20,2
0,20,0,20,20,20,20,20,20,20,20,20,20,20,20,0};
 94
ARRAY,80,41,{2.3,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0,0};
 95
ARRAY,81,41,{10,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,
0,0,0};
 96
ARRAY,82,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
 97
ARRAY,83,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
 98
ARRAY,84,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
 99
ARRAY,85,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
 100 ARRAY,86,1,{999};
 101 TIMST,,LL[40],"P_9",0,0.0,1.0;
 102 TIMST,,LL[41],"P_10",0,0.0,1.0;
 103 TIMST,,LL[42],"P_11",0,0.0,1.0;
 104 TIMST,,LL[43],"P_12",0,0.0,1.0;
 105 TIMST,,LL[1],"ORDER_COST",0,0.0,1.0;
 106 TIMST,,LL[2],"EOQ_ORDERS",0,0.0,1.0;
 107 TIMST,,LL[3],"MRP_ORDERS",0,0.0,1.0;
 108 TIMST,,LL[4],"TOT_PROD",0,0.0,1.0;
 109 TIMST,,ARRAY[1,2],"PRODUCTION",0,0.0,1.0;
 110 TIMST,,NNRSC(1),"PART1",0,0.0,1.0;
 111 TIMST,,NNRSC(2),"PART2",0,0.0,1.0;
```

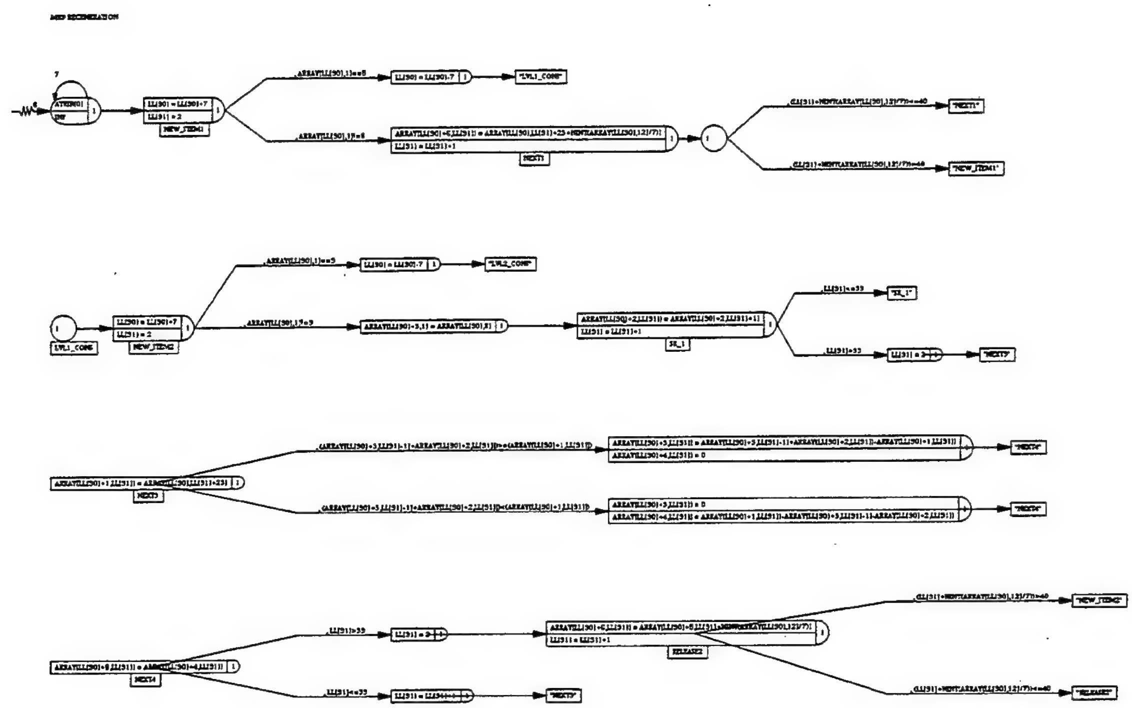
```
TIMST,,NNRSC(3),"PART3",0,0.0,1.0;
TIMST,,NNRSC(4),"PART4",0,0.0,1.0;
TIMST,,NNRSC(5),"PART5",0,0.0,1.0;
TIMST,,NNRSC(6),"PART6",0,0.0,1.0;
TIMST,,NNRSC(7),"PART7",0,0.0,1.0;
TIMST,,NNRSC(8),"PART8",0,0.0,1.0;
TIMST,,NNRSC(9),"PART9",0,0.0,1.0;
TIMST,,NNRSC(10),"PART10",0,0.0,1.0;
TIMST,,NNRSC(11),"PART11",0,0.0,1.0;
TIMST,,NNRSC(12),"PART12",0,0.0,1.0;
NETWORK,READ;
FIN;
```

MODEL 2: Visual SLAM Model Components

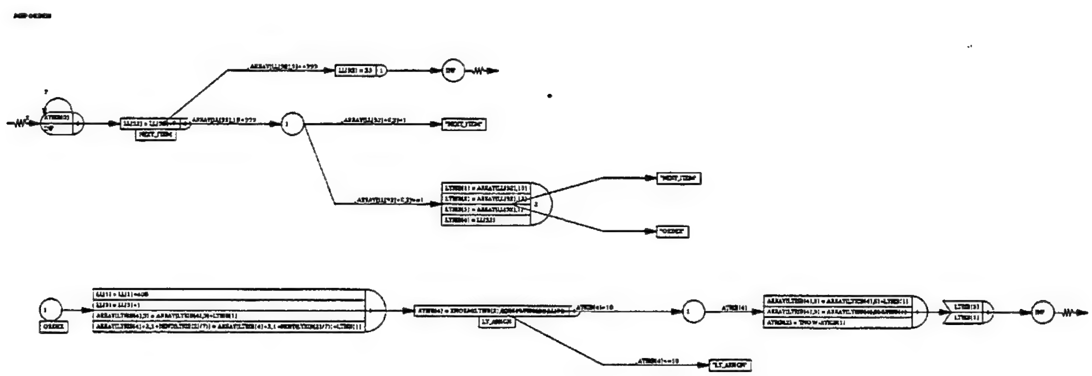
Only those processes unique to Model 2 are presented below. The front and backshop repair processes, for example, are identical to those of Model 1 and are therefore omitted for brevity.



On a weekly basis, a 39-week production schedule is generated using the projected quarterly end-item production from row 1 of the array. Material requirements are evenly distributed across the weeks in a quarter.



The MRP regeneration process is conducted each week, and begins with the assignment of gross requirements for each item based on end-item forecasts. Next, the on-hand balance is updated in the MRP array. The scheduled receipts row of each item is then shifted to the left to reflect current expected receipts. Finally, the net requirement for each item for each week is calculated by comparing the on-hand plus scheduled receipts to the gross requirement. If the net requirement is greater than zero, planned order receipts are scheduled and planned order releases are calculated by offsetting the receipts by the mean lead time. This process is repeated for each item at each level.



On a weekly basis, the planned order release cell of the array for each item is checked. If there is a positive value in the cell, it indicates that an order needs to be placed and an order is initiated. Similar to Model 1, attributes are stored to reflect the order quantity, part number, and mean lead time before the entity is copied and sent to the order sub-process for action. The part is then ordered and received, and the on-hand and backorder balances are updated.

MODEL 2: Network Source Code

```
RESOURCE,9,CONS5,72,{9};
RESOURCE,10,CONS6,22,{10};
RESOURCE,11,CONS7,425,{11};
RESOURCE,12,CONS8,410,{12};
RESOURCE,1,REP1,15,{1};
RESOURCE,2,REP2,250,{2};
RESOURCE,3,REP3,500,{3};
RESOURCE,4,REP4,15,{4};
RESOURCE,5,CONS1,40,{5};
RESOURCE,6,CONS2,260,{6};
RESOURCE,7,CONS3,5000,{7};
RESOURCE,8,CONS4,6800,{8};
;BACKSHOP REPAIR PROCESSES
;MODULE REPAIR PROCESS: FRONT SHOP
PART1: GOON,LTRIB[10];
ACTIVITY;
ASSIGN,{{LTRIB[18],NINT(TRIAG(0,ARRAY[59,1],ARRAY[60,1],LL[7]))}},1;
ACTIVITY,,,PROB(0.99);
ACTIVITY,,,PROB(0.01),"THESIS1_ASSIGN_1";
ASSIGN,{{LTRIB[19],0}},1;
ACTIVITY;
THESIS1_GOON_1: GOON,1;
ACTIVITY,,,LTRIB[18]>=1;
ACTIVITY,,,LTRIB[18]<1,"PN_10";
ASSIGN,{{ARRAY[58,8],ARRAY[58,8]-LTRIB[18]}},1;
ACTIVITY;
MODEL_1_AWAIT_1: AWAIT,9,{{CONS5,LTRIB[18]}},ALL,,NONE,1;
ACTIVITY;
ASSIGN,{{ARRAY[58,2],ARRAY[58,2]+LTRIB[18]}},1;
ACTIVITY,,,,"PN_10";
PN_10: GOON,1;
ACTIVITY,,,LTRIB[19]>=1;
ACTIVITY,,,LTRIB[19]<1,"FIX_REP1";
ASSIGN,{{ARRAY[65,8],ARRAY[65,8]-LTRIB[19]}},1;
ACTIVITY;
MODEL_1_AWAIT_2: AWAIT,10,{{CONS6,LTRIB[19]}},ALL,,NONE,1;
ACTIVITY;
ASSIGN,{{ARRAY[65,2],ARRAY[65,2]+LTRIB[19]}},1;
ACTIVITY,,,,"FIX_REP1";
THESIS1_ASSIGN_1: ASSIGN,{{LTRIB[19],1}},1;
ACTIVITY,,,,"THESIS1_GOON_1";
INDUCTIONS: CREATE,91/ARRAY[1,25],0.0,ATRIB[0],INF,1;
ACTIVITY,,,PROB(0.3);
ACTIVITY,,,PROB(0.7),"MODEL_1_ASSIGN_3";
OVERHAUL: GOON,1;
ACTIVITY,,,ARRAY[LL[86],5]<=2;
```

```
ACTIVITY,,,ARRAY[LL[86],5]>2,"MODEL_1_ASSIGN_2";
ASSIGN,{{LTRIB[LL[84]],ARRAY[LL[86],5]}},1;
ACTIVITY;
MODEL_1_ASSIGN_1: ASSIGN,{{LL[84],LL[84]+1},{LL[86],LL[86]+7}},1;
ACTIVITY,,,ARRAY[LL[86],1]!=9,"OVERHAUL";
ACTIVITY,,,ARRAY[LL[86],1]==9;
ASSIGN,{{LL[84],10},{LL[86],2}},1;
ACTIVITY,,,,"PN_1";
MODEL_1_ASSIGN_2: ASSIGN,{{LTRIB[LL[84]],NINT(UNFRM(ARRAY[LL[86]+1,1],ARRAY[LL[86]+2,1],LL[7]))}},1;
ACTIVITY,,,,"MODEL_1_ASSIGN_1";
MODEL_1_ASSIGN_3: ASSIGN,{{LTRIB[10],0},{LTRIB[11],0},{LTRIB[12],0},{LTRIB[13],0},{LTRIB[14],0},{LTRIB[15],0},{LTRIB[16],0},{LTRIB[17],0}},1;
ACTIVITY;
OCM: ASSIGN,{{LTRIB[30],INT(UNFRM(1,9,LL[7]))},{LTRIB[31],INT(UNFRM(1,9,LL[7]))}},1;
ACTIVITY,,,LTRIB[30]==LTRIB[31],"OCM";
ACTIVITY,,,LTRIB[30]!=LTRIB[31],"QTY";
FIX_REP1: GOON,1;
ACTIVITY,,ARRAY[2,7];
ALTER,REP1,1,1;
ACTIVITY;
WRITE,"repair.dat",NO,,{"REP1",TNOW},1;
ACTIVITY,,,,"END_REPAIR";
END_REPAIR: TERMINATE,INF;
PART2: GOON,LTRIB[11];
ACTIVITY;
ASSIGN,{{LTRIB[20],NINT(TRIAG(0,ARRAY[73,1],ARRAY[74,1],LL[7]))},{LTRIB[21],NINT(TRIAG(1,ARRAY[80,1],ARRAY[81,1],LL[7]))}},1;
ACTIVITY,,,LTRIB[20]>=1;
ACTIVITY,,,LTRIB[20]<1,"PN_12";
ASSIGN,{{ARRAY[72,8],ARRAY[72,8]-LTRIB[20]}},1;
ACTIVITY;
MODEL_1_AWAIT_3: AWAIT,11,{{CONS7,LTRIB[20]}},ALL,,NONE,1;
ACTIVITY;
ASSIGN,{{ARRAY[72,2],ARRAY[72,2]+LTRIB[20]}},1;
ACTIVITY;
WRITE,"part11.dat",NO,,{TNOW,LTRIB[20],ARRAY[72,2]},1;
ACTIVITY,,,,"PN_12";
PN_12: GOON,1;
ACTIVITY,,,LTRIB[21]>=1;
ACTIVITY,,,LTRIB[21]<1,"FIX_REP2";
ASSIGN,{{ARRAY[79,8],ARRAY[79,8]-LTRIB[21]}},1;
ACTIVITY;
MODEL_1_AWAIT_4: AWAIT,12,{{CONS8,LTRIB[21]}},ALL,,NONE,1;
ACTIVITY;
```

```
ASSIGN,{{ARRAY[79,2],ARRAY[79,2]+LTRIB[21]}},1;
ACTIVITY,,,,"FIX_REP2";
QTY: GOON,1;
ACTIVITY,,,ARRAY[(LTRIB[30]+1)+(6*(LTRIB[30]-1)),5]<=2;
ACTIVITY,,,ARRAY[(LTRIB[30]+1)+(6*(LTRIB[30]-1)),5]>2,"MODEL_1_ASSIGN_5";
ASSIGN,{{LTRIB[LTRIB[30]+9],ARRAY[(LTRIB[30]+1)+(6*(LTRIB[30]-1)),5]}},1;
ACTIVITY;
MODEL_1_GOON_1: GOON,1;
ACTIVITY,,,ARRAY[(LTRIB[31]+1)+(6*(LTRIB[31]-1)),5]<=2;
ACTIVITY,,,ARRAY[(LTRIB[31]+1)+(6*(LTRIB[31]-1)),5]>2,"MODEL_1_ASSIGN_4";
ASSIGN,{{LTRIB[LTRIB[31]+9],ARRAY[(LTRIB[31]+1)+(6*(LTRIB[31]-1)),5]}},1;
ACTIVITY,,,,"PN_1";
MODEL_1_ASSIGN_4: ASSIGN,{{LTRIB[51],(LTRIB[31]+1)+(6*(LTRIB[31]-1))},{LTRIB[LTRIB[31]+9],NINT(UNFRM(ARRAY[LTRIB[51]+1,1],ARRAY[LTRIB[51]+2,1],LL[7]))}},1;
ACTIVITY,,,,"PN_1";
MODEL_1_ASSIGN_5: ASSIGN,{{LTRIB[50],(LTRIB[30]+1)+(6*(LTRIB[30]-1))},{LTRIB[LTRIB[30]+9],NINT(UNFRM(ARRAY[LTRIB[50]+1,1],ARRAY[LTRIB[50]+2,1],LL[7]))}},1;
ACTIVITY,,,,"MODEL_1_GOON_1";
FIX_REP2: GOON,1;
ACTIVITY,,ARRAY[9,7];
ALTER,REP2,1,1;
ACTIVITY;
WRITE,"repair.dat",NO,,{"REP2",TNOW},1;
ACTIVITY,,,,"END_REPAIR";
PART3: GOON,1;
ACTIVITY,,ARRAY[16,7];
ALTER,REP3,LTRIB[12],1;
ACTIVITY;
WRITE,"repair.dat",NO,,{"REP3",TNOW},1;
ACTIVITY,,,,"END_REPAIR";
PN_1: GOON,1;
ACTIVITY,,,LTRIB[10]>=1;
ACTIVITY,,,LTRIB[10]<1,"PN_2";
GOON,2;
ACTIVITY,,,,"PART1";
ACTIVITY;
AWAIT,1,{{REP1,LTRIB[10]}},ALL,,NONE,1;
ACTIVITY,,,,"PN_2";
PN_2: GOON,1;
ACTIVITY,,,LTRIB[11]>=1;
ACTIVITY,,,LTRIB[11]<1,"PN_3";
GOON,2;
ACTIVITY,,,,"PART2";
ACTIVITY;
AWAIT,2,{{REP2,LTRIB[11]}},ALL,,NONE,1;
ACTIVITY,,,,"PN_3";
PN_3: GOON,1;
```

```
ACTIVITY,,,LTRIB[12]>=1;
ACTIVITY,,,LTRIB[12]<1,"PN_4";
GOON,2;
ACTIVITY,,,,"PART3";
ACTIVITY;
AWAIT,3,{{REP3,LTRIB[12]}},ALL,,NONE,1;
ACTIVITY,,,,"PN_4";
PN_4: GOON,1;
ACTIVITY,,,LTRIB[13]>=1;
ACTIVITY,,,LTRIB[13]<1,"PN_5";
GOON,2;
ACTIVITY,,,,"PART4";
ACTIVITY;
AWAIT,4,{{REP4,LTRIB[13]}},ALL,,NONE,1;
ACTIVITY,,,,"PN_5";
PART4: GOON,LTRIB[13];
ACTIVITY,,ARRAY[23,7];
ALTER,REP4,1,1;
ACTIVITY;
WRITE,"repair.dat",NO,,{"REP4",TNOW},1;
ACTIVITY,,,,"END_REPAIR";
FIX: GOON,1;
ACTIVITY,,ARRAY[1,7],,,,"END-ITEM FIX";
ASSIGN,{{ARRAY[1,2],ARRAY[1,2]+1},{LL[4],LL[4]+1}},1;
ACTIVITY;
TERMINATE,INF;
PN_5: GOON,1;
ACTIVITY,,,LTRIB[14]>=1;
ACTIVITY,,,LTRIB[14]<1,"PN_6";
GOON,1;
ACTIVITY;
ASSIGN,{{ARRAY[30,8],ARRAY[30,8]-LTRIB[14]}},1;
ACTIVITY;
MODEL_1_AWAIT_5: AWAIT,5,{{CONS1,LTRIB[14]}},ALL,,NONE,1;
ACTIVITY;
ASSIGN,{{ARRAY[30,2],ARRAY[30,2]+LTRIB[14]}},1;
ACTIVITY,,,,"PN_6";
PN_6: GOON,1;
ACTIVITY,,,LTRIB[15]>=1;
ACTIVITY,,,LTRIB[15]<1,"PN_7";
GOON,1;
ACTIVITY;
ASSIGN,{{ARRAY[37,8],ARRAY[37,8]-LTRIB[15]}},1;
ACTIVITY;
MODEL_1_AWAIT_6: AWAIT,6,{{CONS2,LTRIB[15]}},ALL,,NONE,1;
ACTIVITY;
ASSIGN,{{ARRAY[37,2],ARRAY[37,2]+LTRIB[15]}},1;
ACTIVITY,,,,"PN_7";
PN_7: GOON,1;
```

```
ACTIVITY,,,LTRIB[16]>=1;
ACTIVITY,,,LTRIB[16]<1,"PN_8";
GOON,1;
ACTIVITY;
ASSIGN,{{ARRAY[44,8],ARRAY[44,8]-LTRIB[16]}},1;
ACTIVITY;
MODEL_1_AWAIT_7: AWAIT,7,{{CONS3,LTRIB[16]}},ALL,,NONE,1;
ACTIVITY;
ASSIGN,{{ARRAY[44,2],ARRAY[44,2]+LTRIB[16]}},1;
ACTIVITY,,,,"PN_8";
PN_8: GOON,1;
ACTIVITY,,,LTRIB[17]>=1;
ACTIVITY,,,LTRIB[17]<1,"FIX";
GOON,1;
ACTIVITY;
ASSIGN,{{ARRAY[51,8],ARRAY[51,8]-LTRIB[17]}},1;
ACTIVITY;
MODEL_1_AWAIT_8: AWAIT,8,{{CONS4,LTRIB[17]}},ALL,,NONE,1;
ACTIVITY;
ASSIGN,{{ARRAY[51,2],ARRAY[51,2]+LTRIB[17]}},1;
ACTIVITY,,,,"FIX";
;EOQ CALCULATION
CREATE,90,91,ATRIB[0],INF,1;
ACTIVITY,,,,"ANNUAL_DEMAND";
ANNUAL_DEMAND:
ASSIGN,{{XX[81],ARRAY[LL[60],21]+ARRAY[LL[60],22]+ARRAY[LL[60],23]+ARRAY[LL
[60],24]},{XX[82],ARRAY[LL[60],17]+ARRAY[LL[60],18]+ARRAY[LL[60],19]+ARRAY[LL[
60],20]},{XX[83],(XX[81]+XX[82])/2}},1;
ACTIVITY;
EOQ_AND_ROP:
ASSIGN,{{ARRAY[LL[60],10],INT(SQRT((2*ARRAY[LL[60],16]*XX[83])/ARRAY[LL[60],1
5])+0.5)},{ARRAY[LL[60],11],(INT(((XX[83])/365)*(ARRAY[LL[60],12])+0.5))}},1;
ACTIVITY;
WRITE,"eoq_calc.dat",NO,,{TNOW,ARRAY[LL[60],1],XX[83],ARRAY[LL[60],10],ARRAY[
LL[60],11]},1;
ACTIVITY;
COUNTER: ASSIGN,{{LL[60],LL[60]+7}},1;
ACTIVITY,,,ARRAY[LL[60],1]==999;
ACTIVITY,,,ARRAY[LL[60],1]!=999,"ANNUAL_DEMAND";
ASSIGN,{{LL[60],30}},1;
ACTIVITY;
TERMINATE,INF;
;EOQ ORDERS
CREATE,7,0.0,ATRIB[0],INF,1;
ACTIVITY;
NEXT_ITEM: ASSIGN,{{LL[91],LL[91]+7}},1;
ACTIVITY,,,ARRAY[LL[91],1]==999;
ACTIVITY,,,ARRAY[LL[91],1]!=999,"THESIS1_WRITE_1";
```

```
ASSIGN,{{LL[91],23}},1;
ACTIVITY;
TERMINATE,INF;
THESIS1_WRITE_1: WRITE,"order.dat",NO,,{ARRAY[LL[91],1],ARRAY[LL[91],8],ARRAY[LL[91],9],ARRAY[LL[91],11]},1;
ACTIVITY;
THESIS1_GOON_4: GOON,1;
ACTIVITY,,,(ARRAY[LL[91],8]+ARRAY[LL[91],9])>ARRAY[LL[91],11],"NEXT_ITEM";
ACTIVITY,,,(ARRAY[LL[91],8]+ARRAY[LL[91],9])<=ARRAY[LL[91],11];
ASSIGN,{{LTRIB[5],ARRAY[LL[91],12]},{LTRIB[6],ARRAY[LL[91],1]},{LTRIB[7],LL[91]},{LTRIB[8],ARRAY[LL[91],10]}},2;
ACTIVITY,,,,"NEXT_ITEM";
ACTIVITY,,,,"ORDER";
ORDER: GOON,1;
ACTIVITY;
WRITE,"eoq_order.dat",NO,,{TNOW,LTRIB[6],LTRIB[8],ARRAY[LTRIB[7],8],ARRAY[LTRIB[7],11] },1;
ACTIVITY;
ASSIGN,{{ATRIB[3],TNOW}},1;
ACTIVITY;
ASSIGN,{{ARRAY[LTRIB[7],9],ARRAY[LTRIB[7],9]+LTRIB[8]},{LL[1],LL[1]+405},{LL[2],LL[2]+1}},1;
ACTIVITY;
LT_ASSIGN: ASSIGN,{{ATRIB[4],RNORM(LTRIB[5],(XX[6]*LTRIB[5]),LL[7])}},1;
ACTIVITY,,,ATRIB[4]>10;
ACTIVITY,,,ATRIB[4]<=10,"LT_ASSIGN";
GOON,1;
ACTIVITY,,ATRIB[4];
WRITE,"charlene.dat",NO,,{LTRIB[6],LTRIB[5],LTRIB[8],TNOW},1;
ACTIVITY;
ASSIGN,{{ARRAY[LTRIB[7],8],ARRAY[LTRIB[7],8]+LTRIB[8]},{ARRAY[LTRIB[7],9],ARRAY[LTRIB[7],9]-LTRIB[8]}},1;
ACTIVITY;
ALTER,LTRIB[6],LTRIB[8],1;
ACTIVITY;
TERMINATE,INF;
;PRODUCTION AND INVENTORY PLAN
CREATE,91,91,ATRIB[0],INF,1;
ACTIVITY;
WRITE,"prod.dat",NO,,{TNOW,ARRAY[1,2]},1;
ACTIVITY;
ASSIGN,{{LL[80],1}},1;
ACTIVITY;
```

```
263 START_1:
ASSIGN,{{ARRAY[1,16+LL[80]],ARRAY[1,17+LL[80]]},{LL[80],LL[80]+1}},1;
264 ACTIVITY,,,LL[80]<=7,"START_1";
265 ACTIVITY,,,LL[80]>7;
266
ASSIGN,{{ARRAY[1,16+LL[80]],ARRAY[1,2]},{ARRAY[1,2],0},{ARRAY[1,17+LL[80]],AR
RAY[1,18+LL[80]]},{LL[80],LL[80]+1}},1;
267 ACTIVITY,,,,"FUTURE";
268 FUTURE: GOON,1;
269 ACTIVITY;
270 START_2: ASSIGN,{{ARRAY[1,16+LL[80]],ARRAY[1,17+LL[80]]+NINT(UNFRM(-
LL[5],LL[5],LL[7]))},{LL[80],LL[80]+1}},1;
271 ACTIVITY,,,LL[80]<=15,"START_2";
272 ACTIVITY,,,LL[80]>15,"NEW_QTR";
273 NEW_QTR: GOON,1;
274 ACTIVITY;
275
ASSIGN,{{ARRAY[1,17+LL[80]],NINT(TRIAG(XX[8],XX[9],XX[10],LL[7]))},{LL[80],1}},1;
276 ACTIVITY,,,,"PARTS";
277 PARTS: GOON,1;
278 ACTIVITY;
279 NEW_ITEMS: ASSIGN,{{LL[79],LL[79]+7},{LL[80],1}},1;
280 ACTIVITY,,,ARRAY[LL[79],1]==9,"LEVEL_2";
281 ACTIVITY,,,ARRAY[LL[79],1]!=9,"NEXT_COL";
282 NEXT_COL:
ASSIGN,{{ARRAY[LL[79],16+LL[80]],ARRAY[LL[79],17+LL[80]]},{LL[80],LL[80]+1}},1;
283 ACTIVITY,,,LL[80]<=7,"NEXT_COL";
284 ACTIVITY,,,LL[80]>7;
285 ASSIGN,{{ARRAY[LL[79],16+LL[80]],ARRAY[LL[79],2]},{ARRAY[LL[79],2],0}},1;
286 ACTIVITY;
287
WRITE,"parts.dat",NO,,{TNOW,ARRAY[LL[79],1],ARRAY[LL[79],17],ARRAY[LL[79],18],
ARRAY[LL[79],19],ARRAY[LL[79],20],ARRAY[LL[79],21],ARRAY[LL[79],22],ARRAY[LL[
79],23],ARRAY[LL[79],24]},1;
288 ACTIVITY,,,,"NEW_ITEMS";
289 LEVEL_2: GOON,1;
290 ACTIVITY;
291 NEW_ITEMS2: GOON,1;
292 ACTIVITY,,,ARRAY[LL[79],1]==11,"LEVEL_2_2";
293 ACTIVITY,,,ARRAY[LL[79],1]!=11;
294 NEXT_COL2:
ASSIGN,{{ARRAY[LL[79],16+LL[80]],ARRAY[LL[79],17+LL[80]]},{LL[80],LL[80]+1}},1;
295 ACTIVITY,,,LL[80]<=7,"NEXT_COL2";
296 ACTIVITY,,,LL[80]>7;
297 ASSIGN,{{ARRAY[LL[79],16+LL[80]],ARRAY[LL[79],2]},{ARRAY[LL[79],2],0}},1;
298 ACTIVITY;
299
WRITE,"parts.dat",NO,,{TNOW,ARRAY[LL[79],1],ARRAY[LL[79],17],ARRAY[LL[79],18],
```

```
ARRAY[LL[79],19],ARRAY[LL[79],20],ARRAY[LL[79],21],ARRAY[LL[79],22],ARRAY[LL[
79],23],ARRAY[LL[79],24]},1;
 300 ACTIVITY;
 301 ASSIGN,{{LL[79],LL[79]+7},{LL[80],1}},1;
 302 ACTIVITY,,,,"NEW_ITEMS2";
 303 LEVEL_2_2: GOON,1;
 304 ACTIVITY;
 305 NEW_ITEMS3: GOON,1;
 306 ACTIVITY,,,ARRAY[LL[79],1]==999;
 307 ACTIVITY,,,ARRAY[LL[79],1]!=999,"NEXT_COL3";
 308 ASSIGN,{{LL[79],-5},{LL[80],1}},1;
 309 ACTIVITY;
 310
WRITE,"prod.dat",NO,,{ARRAY[1,17],ARRAY[1,18],ARRAY[1,19],ARRAY[1,20],ARRAY[
1,21],ARRAY[1,22],ARRAY[1,23],ARRAY[1,24],ARRAY[1,25],ARRAY[1,26],ARRAY[1,2
7],ARRAY[1,28],ARRAY[1,29],ARRAY[1,30],ARRAY[1,31],ARRAY[1,32],ARRAY[1,33]},
1;
 311 ACTIVITY;
 312 TERMINATE,INF;
 313 NEXT_COL3:
ASSIGN,{{ARRAY[LL[79],16+LL[80]],ARRAY[LL[79],17+LL[80]]},{LL[80],LL[80]+1}},1;
 314 ACTIVITY,,,LL[80]<=7,"NEXT_COL3";
 315 ACTIVITY,,,LL[80]>7;
 316 ASSIGN,{{ARRAY[LL[79],16+LL[80]],ARRAY[LL[79],2]},{ARRAY[LL[79],2],0}},1;
 317 ACTIVITY;
 318
WRITE,"parts.dat",NO,,{TNOW,LL[79],LL[80],ARRAY[LL[79],1],ARRAY[LL[79],17],ARR
AY[LL[79],18],ARRAY[LL[79],19],ARRAY[LL[79],20],ARRAY[LL[79],21],ARRAY[LL[79],2
2],ARRAY[LL[79],23],ARRAY[LL[79],24]},1;
 319 ACTIVITY;
 320 ASSIGN,{{LL[79],LL[79]+7},{LL[80],1}},1;
 321 ACTIVITY,,,,"NEW_ITEMS3";
 322 CREATE,7,7,ATRIB[0],INF,1;
 323 ACTIVITY;
 324 NEW: ASSIGN,{{LL[70],1},{LL[51],25},{LL[52],0},{LL[69],LL[69]+7}},1;
 325 ACTIVITY,,,ARRAY[LL[69],1]==9,"CURRENT2";
 326 ACTIVITY,,,ARRAY[LL[69],1]!=9,"NXT_QTR";
 327 NXT_QTR: ASSIGN,{{LL[50],1},{LL[52],0}},1;
 328 ACTIVITY;
 329 FUTR:
ASSIGN,{{ARRAY[LL[69],24+LL[70]],NINT((ARRAY[1,LL[51]+INT(ARRAY[LL[69],12]/90
)]*ARRAY[LL[69],6])/13)},{LL[50],LL[50]+1},{LL[52],LL[52]+ARRAY[LL[69],16+LL[70]]},{L
L[70],LL[70]+1}},1;
 330 ACTIVITY,,,LL[50]<=12,"FUTR";
 331 ACTIVITY,,,LL[50]>12,"LAST_WEEK";
 332 LAST_WEEK: GOON,1;
 333 ACTIVITY,,,LL[52]<ARRAY[1,LL[51]+NINT(ARRAY[LL[69],12]/90)];
```

```
334
ACTIVITY,,,LL[52]>=ARRAY[1,LL[51]+NINT(ARRAY[LL[69],12]/90)],"TEST_ASSIGN_11
";
335
ASSIGN,{{ARRAY[LL[69],16+LL[70]],ARRAY[1,LL[51]+NINT(ARRAY[LL[69],12]/90)]-
LL[52]},{LL[70],LL[70]+1},{LL[51],LL[51]+1}},1;
336 ACTIVITY;
337 TEST_GOON_3: GOON,1;
338 ACTIVITY,,,LL[51]>27,"NEW";
339 ACTIVITY,,,LL[51]<=27,"NXT_QTR";
340 TEST_ASSIGN_11:
ASSIGN,{{ARRAY[LL[69],16+LL[70]],0},{LL[70],LL[70]+1},{LL[51],LL[51]+1}},1;
341 ACTIVITY,,,,"TEST_GOON_3";
342 CURRENT2: GOON,1;
343 ACTIVITY,,,ARRAY[LL[69],1]==11,"CURRENT3";
344 ACTIVITY,,,ARRAY[LL[69],1]!=11;
345 FUTR2:
ASSIGN,{{ARRAY[LL[69],24+LL[70]],ARRAY[2,24+LL[70]+INT(ARRAY[LL[69],12]/90)+1
]*ARRAY[LL[69],6]},{LL[70],LL[70]+1}},1;
346 ACTIVITY,,,24+LL[70]+INT(ARRAY[LL[69],12]/90)+1<=63,"FUTR2";
347 ACTIVITY,,,24+LL[70]+INT(ARRAY[LL[69],12]/90)+1>63;
348 ASSIGN,{{LL[69],LL[69]+7},{LL[70],1}},1;
349 ACTIVITY,,,,"CURRENT2";
350 CURRENT3: GOON,1;
351 ACTIVITY,,,ARRAY[LL[69],1]==999;
352 ACTIVITY,,,ARRAY[LL[69],1]!=999,"FUTR3";
353 ASSIGN,{{LL[50],1},{LL[69],-5},{LL[70],1}},1;
354 ACTIVITY;
355 TERMINATE,INF;
356 FUTR3:
ASSIGN,{{ARRAY[LL[69],24+LL[70]],ARRAY[9,24+LL[70]+INT(ARRAY[LL[69],12]/90)+1
]*ARRAY[LL[69],6]},{LL[70],LL[70]+1}},1;
357 ACTIVITY,,,24+LL[70]+INT(ARRAY[LL[69],12]/90)+1<=63,"FUTR3";
358 ACTIVITY,,,24+LL[70]+INT(ARRAY[LL[69],12]/90)+1>63;
359 ASSIGN,{{LL[69],LL[69]+7},{LL[70],1}},1;
360 ACTIVITY,,,,"CURRENT3";
```

MODEL 2: Control Source Code

```
GEN,"Kevin Gaudette","Thesis Test",1 July 1998,1,YES,YES,1;
LIMITS,100,100,,20,60,,5000;
INITIALIZE,0,5110,YES;
MONTR,CLEAR,1460;
INTLC,{{LL[5],0},{XX[6],0},{LL[7],2},{XX[8],63.5},{XX[9],63.5},{XX[10],63.5}};
INTLC,{{LL[44],0}};
INTLC,{{LL[50],1},{LL[51],25},{LL[52],0},{LL[69],-5},{LL[70],1}};
INTLC,{{LL[83],10},{LL[84],10},{LL[85],2},{LL[86],2}};
INTLC,{{LL[60],30},{LL[90],-5},{LL[92],23},{LL[93],-5}};
INTLC,{{LL[1],0},{LL[2],0},{LL[3],0},{LL[4],0},{LL[91],23}};
INTLC,{{LL[79],-5},{LL[80],1}};
INTLC,{{LL[93],-5},{LL[94],1},{LL[95],1}};
INTLC,{{LL[96],-5},{LL[97],1},{LL[98],2},{LL[99],-5},{LL[100],1}};
INTLC,{{LL[81],-5},{LL[82],2}};
ARRAY,1,33,{0,0,0.7,0,0,0,15,0,0,0,0,0,0,231583,0,0,82,44,74,39,71,56,69,61,78,55,59,
76,73,71,61,72,53};
ARRAY,2,63,{1,0,0.8,0,1,0.3,20,27,0,0,0,20,20,1625,0,0,82,44,74,39,71,56,69,61,2,2,2,
2,2,2,2,2,2,2,2,2,2,0,1,1,1,1,1,1,1,1,1,1,1,1,5,1,1,1,1,1,1,1,1,1,1,1,1,6};
ARRAY,3,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,
0,0};
ARRAY,4,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,
0,0};
ARRAY,5,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,
0,0};
ARRAY,6,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,
0,0};
ARRAY,7,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,
0,0};
ARRAY,8,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,
0,0};
ARRAY,9,63,{2,0,0.8,0,1,0.86,7,12,0,0,0,7,7,16875,0,0,82,44,74,39,71,56,69,61,5,5,5,5,
5,5,5,5,5,5,5,5,7,4,4,4,4,4,4,4,4,4,4,4,4,0,4,4,4,4,4,4,4,4,4,4,4,4,3};
ARRAY,10,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
```

25
ARRAY,11,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
26
ARRAY,12,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
27
ARRAY,13,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
28
ARRAY,14,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
29
ARRAY,15,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
30
ARRAY,16,63,{3,0,1,0,80,22,27,500,0,0,0,27,27,147,0,0,1805,969,1629,859,1563,1233,
1519,1343,132,132,132,132,132,132,132,132,132,132,132,132,132
,93,93,93,93,93,93,93,93,93,93,93,93,94,100,100,100,100
,100,100,100,100,100,100,100 ,100,98};
31
ARRAY,17,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
32
ARRAY,18,41,{44,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,
0,0,0};
33
ARRAY,19,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
34
ARRAY,20,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
35
ARRAY,21,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
36
ARRAY,22,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
37
ARRAY,23,63,{4,0,1,0,1,0.88,23,29,0,0,0,23,23,9089,0,0,82,44,74,39,71,56,69,61,5,5,5,
5,5,5,5,5,5,5 ,5,5,9,4,4,4,4,4,4,4,4,4,4,4,4,4,0,4,4,4,4,4,4,4,4,4,4,4,4,4};
38
ARRAY,24,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
39
ARRAY,25,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};

```
40
ARRAY,26,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
41
ARRAY,27,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
42
ARRAY,28,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
43
ARRAY,29,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
44
ARRAY,30,63,{5,0,49,0,2,1.5,0,1100,0,221,46,95,95,17,2.89,405,58,31,52,27,50,39,49,
43,6,6,6,6,6,6,6,6,6,6,6,6,11,7,7,7,7,7,7,7,7,7,7,7,7,5,9,9,9,9,9,9,9,9,9,9,9,6};
45
ARRAY,31,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
46
ARRAY,32,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
47
ARRAY,33,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
48
ARRAY,34,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
49
ARRAY,35,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
50
ARRAY,36,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
51
ARRAY,37,63,{6,0,250,0,16,5,0,3900,0,1182,185,115,115,2,0.34,405,194,104,175,92,1
68,133,163,144,21,21,21,21,21,21,21,21,21,21,21,21,23,23,23,23,23,23,23,23,23,23,23,
23,23,19,29,29,29,29,29,29,29,29,29,29,29,29,32};
52
ARRAY,38,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
53
ARRAY,39,41,{10,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,
0,0,0};
54
ARRAY,40,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
55
ARRAY,41,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
```

56
ARRAY,42,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
57
ARRAY,43,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
58
ARRAY,44,63,{7,0,1216,0,75,60,0,9500,0,5803,3640,188,188,1,0.17,405,2337,1254,21
09,1111,2093,1596,1966,1738,272,272,272,272,272,272,272,272,272,272,272,276,
351,351,351,351,351,351,351,351,351,351,351,351,348,337,337,337,337,337,337,337,
337,337,337,337,337,336};
59
ARRAY,45,41,{45,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,
0,0,0};
60
ARRAY,46,41,{75,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,
0,0,0};
61
ARRAY,47,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
62
ARRAY,48,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
63
ARRAY,49,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
64
ARRAY,50,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
65
ARRAY,51,63,{8,0,1459,0,80,76,0,9200,0,2666,5052,206,206,6,1.02,405,2960,1588,26
71,1407,2563,2021,2490,2202,345,345,345,345,345,345,345,345,345,345,345,344,
444,444,444,444,444,444,444,444,444,444,444,444,448,427,427,427,427,427,427,427,
427,427,427,427,427,424};
66
ARRAY,52,41,{72,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,
0,0,0};
67
ARRAY,53,41,{80,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,
0,0,0};
68
ARRAY,54,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
69
ARRAY,55,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
70
ARRAY,56,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};

71
ARRAY,57,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
72
ARRAY,58,63,{9,0,73,0,6,3,0,212,0,256,20,105,125,5,0.85,405,23,12,21,11,20,15,19,17
,1,1,1,1,1,1,1,1,1,1,1,1,0,1,1,1,1,1,1,1,1,1,1,1,1,0,1,1,1,1,1,1,1,1,1,1,1,1,0};
73
ARRAY,59,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
74
ARRAY,60,41,{6,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
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75
ARRAY,61,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
76
ARRAY,62,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
77
ARRAY,63,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
78
ARRAY,64,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
79
ARRAY,65,63,{10,0,25,0,1,0.01,0,5,0,80,2,142,162,3,0.51,405,1,1,1,1,1,1,1,1,1,1,1,1,1,
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80
ARRAY,66,41,{0.53,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,
0,0,0,0};
81
ARRAY,67,41,{1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
82
ARRAY,68,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
83
ARRAY,69,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
84
ARRAY,70,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
85
ARRAY,71,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
86
ARRAY,72,63,{11,0,146,0,16,5,0,3874,0,345,125,121,128,15,2.55,405,124,66,112,59,1
07,85,104,92,16,16,16,16,16,16,16,16,16,16,16,16,0,16,16,16,16,16,16,16,16,16,16,16,
16,0,16,16,16,16,16,16,16,16,16,16,16,16,0};

```
 87
ARRAY,73,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
 88
ARRAY,74,41,{16,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,
0,0,0};
 89
ARRAY,75,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
 90
ARRAY,76,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
 91
ARRAY,77,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
 92
ARRAY,78,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
 93
ARRAY,79,63,{12,0,122,0,10,4,0,2000,0,374,211,164,171,16,2.72,405,155,83,140,74,1
34,106,131,115,20,20,20,20,20,20,20,20,20,20,20,20,0,20,20,20,20,20,20,20,20,20,2
0,20,0,20,20,20,20,20,20,20,20,20,20,20,20,0};
 94
ARRAY,80,41,{2.3,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0,0};
 95
ARRAY,81,41,{10,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,
0,0,0};
 96
ARRAY,82,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
 97
ARRAY,83,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
 98
ARRAY,84,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
 99
ARRAY,85,41,{0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0};
 100 ARRAY,86,1,{999};
 101 TIMST,,LL[40],"P_9",0,0.0,1.0;
 102 TIMST,,LL[41],"P_10",0,0.0,1.0;
 103 TIMST,,LL[42],"P_11",0,0.0,1.0;
 104 TIMST,,LL[43],"P_12",0,0.0,1.0;
 105 TIMST,,LL[1],"ORDER_COST",0,0.0,1.0;
 106 TIMST,,LL[2],"EOQ_ORDERS",0,0.0,1.0;
 107 TIMST,,LL[3],"MRP_ORDERS",0,0.0,1.0;
 108 TIMST,,LL[4],"TOT_PROD",0,0.0,1.0;
```

```
TIMST,,ARRAY[1,2],"PRODUCTION",0,0.0,1.0;
TIMST,,NNRSC(1),"PART1",0,0.0,1.0;
TIMST,,NNRSC(2),"PART2",0,0.0,1.0;
TIMST,,NNRSC(3),"PART3",0,0.0,1.0;
TIMST,,NNRSC(4),"PART4",0,0.0,1.0;
TIMST,,NNRSC(5),"PART5",0,0.0,1.0;
TIMST,,NNRSC(6),"PART6",0,0.0,1.0;
TIMST,,NNRSC(7),"PART7",0,0.0,1.0;
TIMST,,NNRSC(8),"PART8",0,0.0,1.0;
TIMST,,NNRSC(9),"PART9",0,0.0,1.0;
TIMST,,NNRSC(10),"PART10",0,0.0,1.0;
TIMST,,NNRSC(11),"PART11",0,0.0,1.0;
TIMST,,NNRSC(12),"PART12",0,0.0,1.0;
NETWORK,READ;
FIN;
```

Appendix C: Determination of Initialization Period

In order to determine the appropriate length of the initialization period, 30 pilot runs were conducted for each system and the results were used to observe the point at which steady state was reached for each part. The initialization period used for the final runs was then the longest initialization period observed across all parts in the pilot runs. For Model 1 (EOQ), the reorder point was used as the measure of steady state, since it is directly tied to past demand and hence is sensitive to the initial values set in the model. When the ROP reaches steady state, it can be assumed that the initialization period has lapsed. The same approach was taken for Model 2 (MRP), but in this case the inventory level of each part over time was examined. Since MRP is insensitive to historical demand, but instead uses forecasts of future demand, steady state can be assumed when the inventory level over time becomes relatively constant.

EOQ Initialization

Figures 32 through 39 below illustrate the mean reorder points over time for each part.

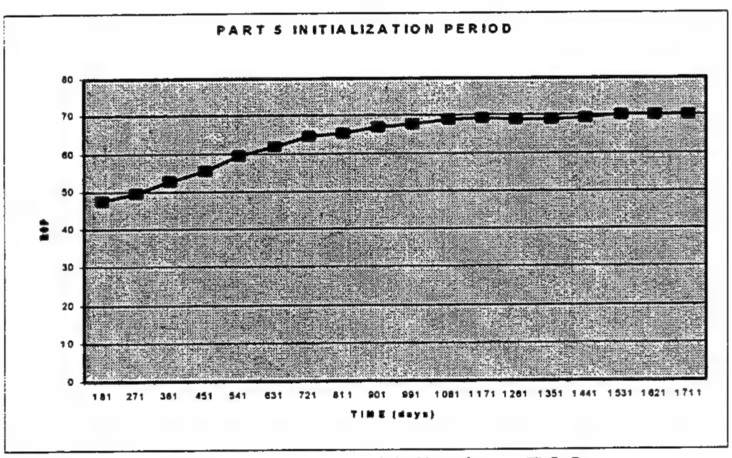

Figure 32: Part 5 Initialization - EOQ

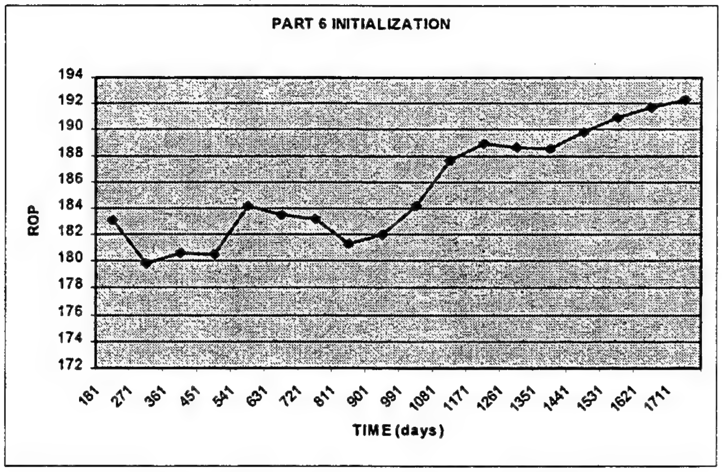

Figure 33: Part 6 Initialization - EOQ

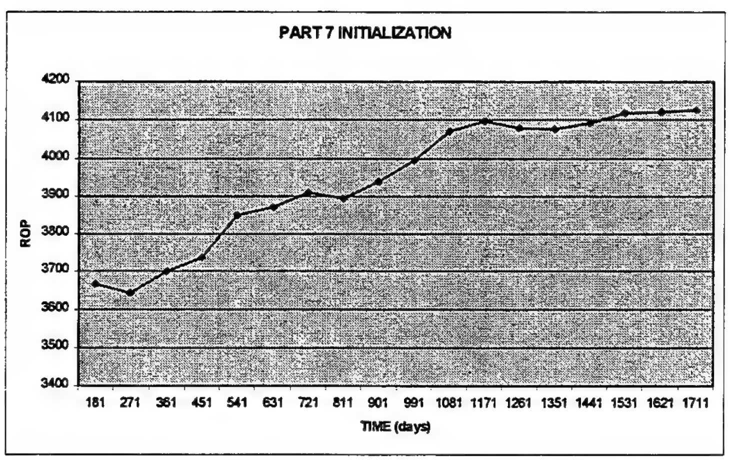

Figure 34: Part 7 Initialization - EOQ

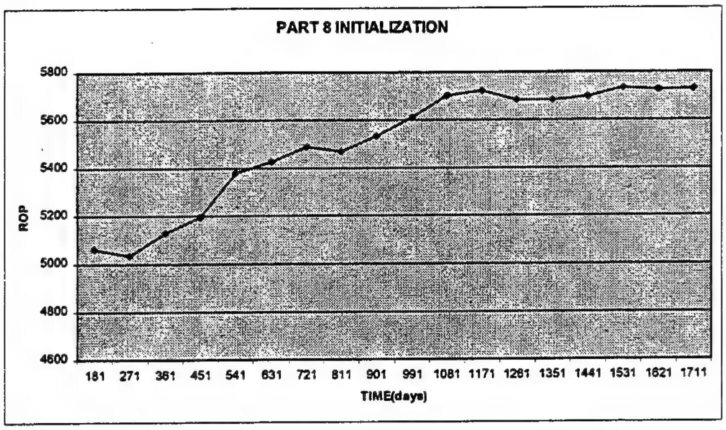

Figure 35: Part 8 Initialization - EOQ

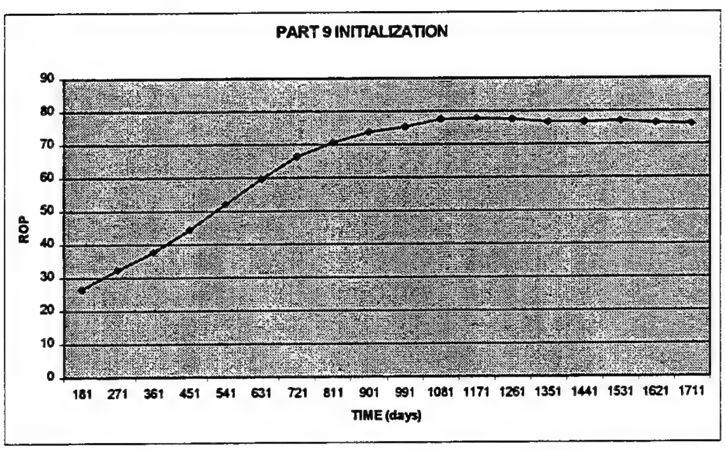

Figure 36: Part 9 Initialization - EOQ

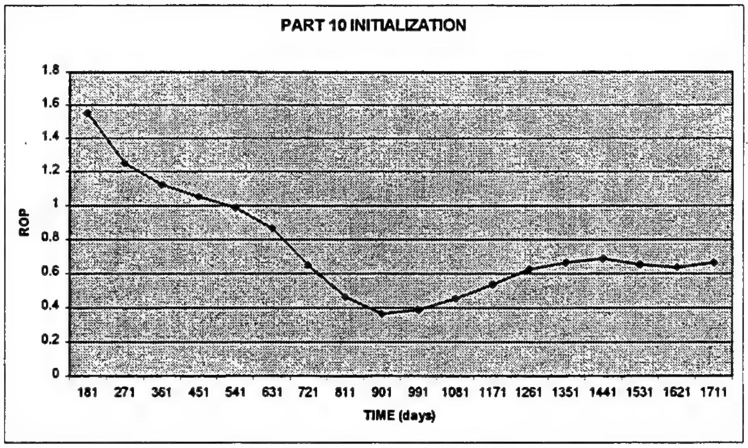

Figure 37: Part 10 Initialization - EOQ

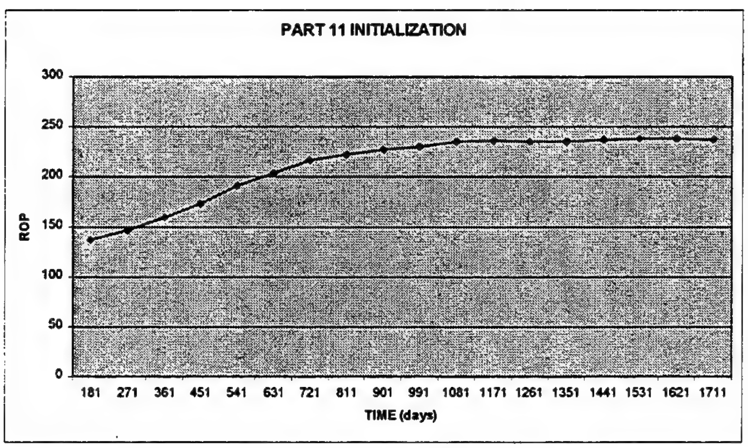

Figure 38: Part 11 Initialization -EOQ

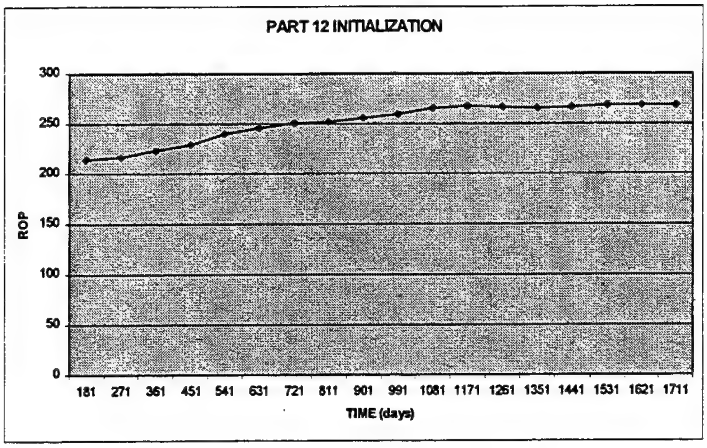

Figure 39: Part 12 Initialization - EOQ

MRP Initialization

Figures 40 through 47 illustrate the mean inventory level for each part over time.

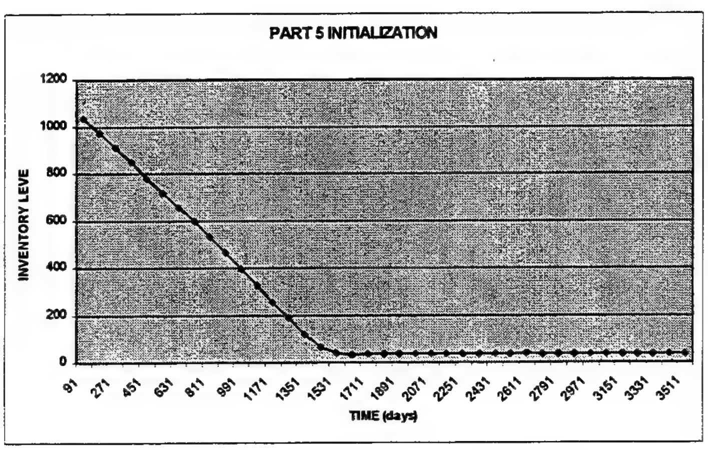

Figure 40: Part 5 Initialization - MRP

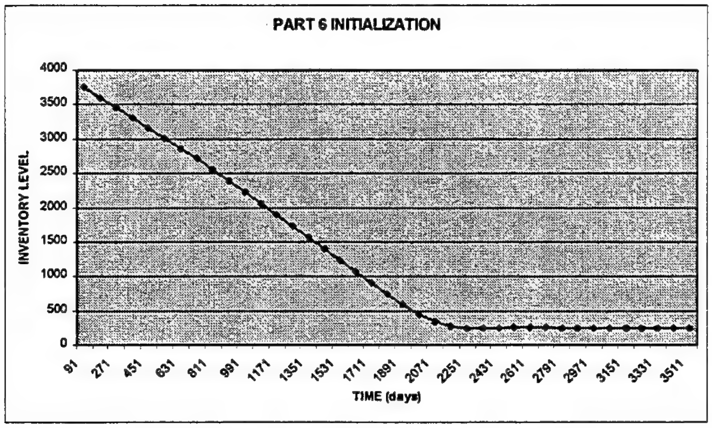

Figure 41: Part 6 Initialization - MRP

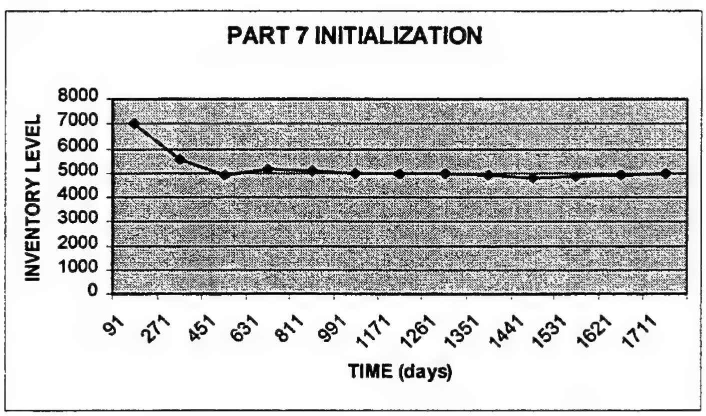

Figure 42: Part 7 Initialization - MRP

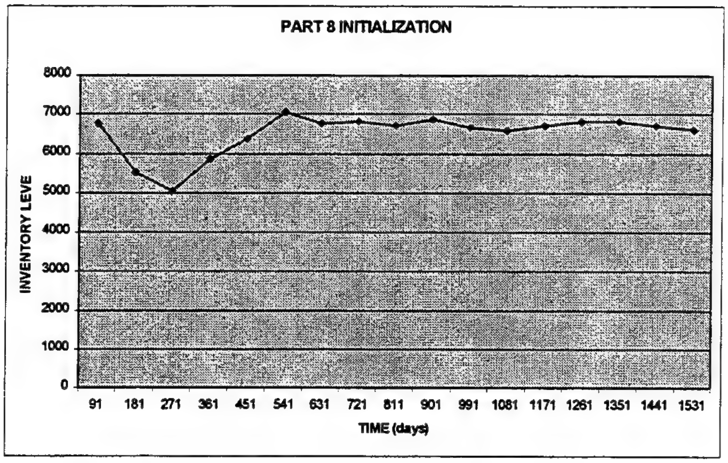

Figure 43: Part 8 Initialization - MRP

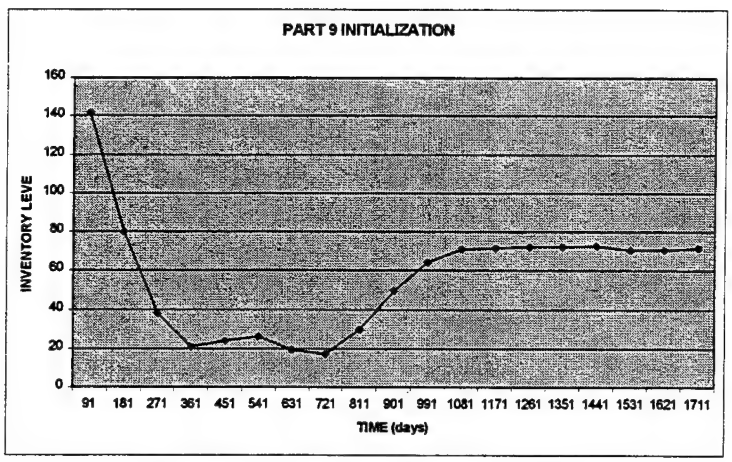

Figure 44: Part 9 Initialization - MRP

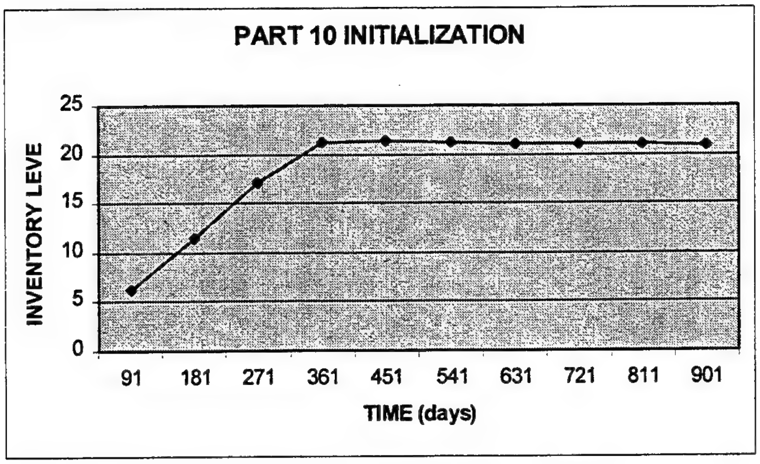

Figure 45: Part 10 Initialization - MRP

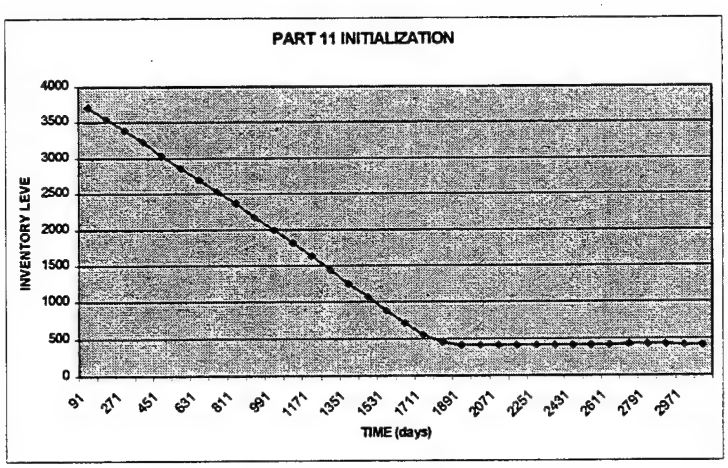

Figure 46: Part 11 Initialization: MRP

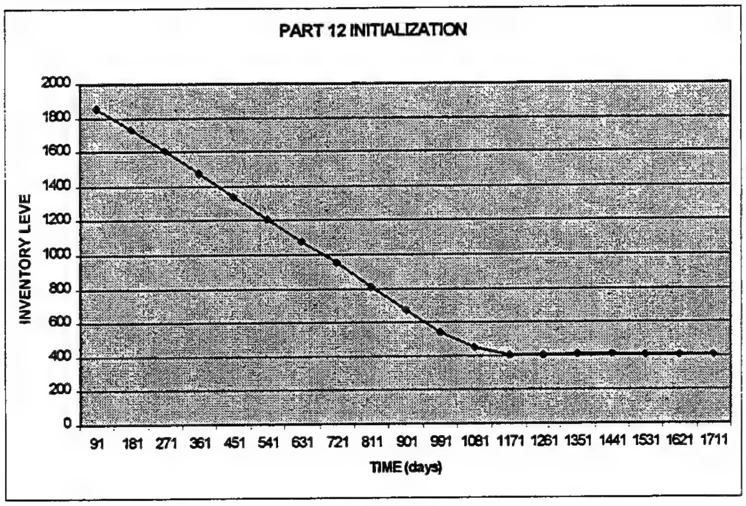

Figure 47: Part 12 Initialization - MRP

Note that the initialization period varies between 1171 and 1261 days for the EOQ model, while the maximum initialization period for the MRP model is over 2000 days. In fact, parts 6 and 11 both showed initialization periods in the MRP that were higher than the maximum experienced in the EOQ model. As such, the initial inventory levels were adjusted down in both cases and the pilot runs were run a second time. In the second iteration, all initialization periods fell below 1171. This figure was then adjusted upward for conservatism, and the resulting value of 1460 (4 years) was used in the model.

Appendix D: Simulation Results

EOQ Model Output

Table 36 below shows the complete results for all replications of the EOQ model, boxed by treatment (10 replications per treatment).

Table 36: Output Data for All Replications - EOQ Model

REP	SYS	D.U.	D.V.	LT VAR.	AWP DAYS	ANNUAL COST
1	1	1	1	1	2.435	8048.11423
2	1	1	1	1	2.796	8198.28334
3	1	1	1	1	3.64	7980.04725
4	1	1	1	1	3.539	8068.54359
5	1	1	1	1	2.763	8031.14415
6	1	1	1	1	4.292	8203.17359
7	1	1	1	1	5.547	8030.68729
8	1	1	1	1	4.885	8074.20855
9	1	1	1	1	3.246	8006.06655
10	1	1	1	1	4.939	8020.30162
11	1	2	1	1	3.053	8000.52188
12	1	2	1	1	3.834	8131.03304
13	1	2	1	1	3.147	7888.02263
14	1	2	1	1	3.836	7981.5279
15	1	2	1	1	3.756	7845.14297
16	1	2	1	1	3.939	8200.2321
17	1	2	1	1	4.518	8101.33013
18	1	2	1	1	5.188	8200.222
19	1	2	1	1	3.288	8127.56203
20	1	2	1	1	5.18	8092.85845
21	1	3	1	1	7.506	7818.3084
22	1	3	1	1	6.931	7967.18447
23	1	3	1	1	4.999	7794.78069
24	1	3	1	1	5.847	8047.42024
25	1	3	1	1	4.971	7829.10823
26	1	3	1	1	5.266	8067.36571
27	1	3	1	1	6.027	8106.98664
28	1	3	1	1	5.219	8151.41641
29	1	3	1	1	6.096	7856.72835
30	1	3	1	1	7.995	8053.7507
31	1	1	2	1	5.825	7978.77495
32	1	1	2	1	5.509	8106.90844

33	1	1	2	1	3.764	8024.37412
34	1	1	2	1	4.416	8105.22374
35	1	1	2	1	3.527	8063.25924
36	1	1	2	1	3.602	8183.79871
37	1	1	2	1	3.07	8010.25307
38	1	1	2	1	3.333	8162.53642
39	1	1	2	1	3.093	7943.62181
40	1	1	2	1	3.971	8214.47186
41	1	2	2	1	6.409	8009.74989
42	1	2	2	1	5.057	8095.50297
43	1	2	2	1	4.2	7876.63047
44	1	2	2	1	4.488	8300.12374
45	1	2	2	1	7.478	7886.6399
46	1	2	2	1	4.585	8089.79046
47	1	2	2	1	6.884	7912.74867
48	1	2	2	1	4.8	8174.04207
49	1	2	2	1	2.986	7779.21607
50	1	2	2	1	4.222	8162.82037
51	1	3	2	1	4.014	7982.74022
52	1	3	2	1	4.248	8253.85015
53	1	3	2	1	7.35	8008.02789
54	1	3	2	1	5.618	8085.20806
55	1	3	2	1	7.064	7961.07214
56	1	3	2	1	3.344	8222.25164
57	1	3	2	1	6.312	8039.40717
58	1	3	2	1	4.83	8075.40414
59	1	3	2	1	3.848	7961.4033
60	1	3	2	1	5.401	8102.36873
61	1	1	3	1	5.274	7761.83447
62	1	1	3	1	3.712	7972.6327
63	1	1	3	1	4.375	8016.94376
64	1	1	3	1	3.659	8036.68746
65	1	1	3	1	5.05	7880.0965
66	1	1	3	1	4.299	8290.75494
67	1	1	3	1	3.014	8032.67699
68	1	1	3	1	3.397	8155.26421
69	1	1	3	1	4.015	7909.83924
70	1	1	3	1	3.443	8081.45701
71	1	2	3	1	5.577	7825.37173
72	1	2	3	1	3.723	8034.87662
73	1	2	3	1	5.924	8066.54466
74	1	2	3	1	3.54	8154.60267
75	1	2	3	1	5.286	8021.13239
76	1	2	3	1	8.782	8160.68862
77	1	2	3	1	4.241	7842.59732
78	1	2	3	1	5.518	8103.24652
79	1	2	3	1	5.71	7834.48718

80	1	2	3	1	4.327	8106.27461
81	1	3	3	1	7.178	7992.78868
82	1	3	3	1	7.619	8241.14105
83	1	3	3	1	4.019	8177.1428
84	1	3	3	1	3.156	8344.50661
85	1	3	3	1	6.782	7898.295
86	1	3	3	1	4.159	8084.93919
87	1	3	3	1	5.651	7900.2059
88	1	3	3	1	5.376	8309.38563
89	1	3	3	1	5.503	7977.94865
90	1	3	3	1	7.693	8177.07589
91	1	1	1	2	7.385	8242.49762
92	1	1	1	2	10.214	8050.39529
93	1	1	1	2	10.686	8174.72634
94	1	1	1	2	13.881	8355.58813
95	1	1	1	2	14.067	7901.09019
96	1	1	1	2	10.585	8042.49073
97	1	1	1	2	15.623	8055.26769
98	1	1	1	2	14.219	8036.17496
99	1	1	1	2	8.407	8286.31218
100	1	1	1	2	7.318	8184.23658
101	1	2	1	2	16.256	8009.74314
102	1	2	1	2	11.88	8198.22151
103	1	2	1	2	15.986	7746.80096
104	1	2	1	2	10.725	8427.36779
105	1	2	1	2	19.552	7996.87708
106	1	2	1	2	9.314	8189.53803
107	1	2	1	2	13.856	8226.75023
108	1	2	1	2	21.172	7879.9581
109	1	2	1	2	13.616	7996.75014
110	1	2	1	2	13.809	8373.73415
111	1	3	1	2	14.386	8051.23747
112	1	3	1	2	16.69	8023.10723
113	1	3	1	2	10.566	8144.99266
114	1	3	1	2	11.091	8112.63921
115	1	3	1	2	11.856	8074.32374
116	1	3	1	2	13.324	8012.35429
117	1	3	1	2	16.385	8119.7982
118	1	3	1	2	11.928	8227.51407
119	1	3	1	2	12.134	8060.20934
120	1	3	1	2	15.015	8417.32271
121	1	1	2	2	12.579	8079.49339
122	1	1	2	2	12.747	8019.21894
123	1	1	2	2	14.208	7786.94607
124	1	1	2	2	11.419	8076.63134
125	1	1	2	2	7.69	8390.84018
126	1	1	2	2	10.995	8021.85564

127	1	1	2	2	13.036	8399.31361
128	1	1	2	2	16.218	8158.19608
129	1	1	2	2	12.416	8312.38047
130	1	1	2	2	12.859	8303.61799
131	1	2	2	2	11.624	7907.34388
132	1	2	2	2	18.366	8084.1936
133	1	2	2	2	11.09	7987.26149
134	1	2	2	2	14.35	8161.76649
135	1	2	2	2	10.702	8119.87259
136	1	2	2	2	13.341	8173.61105
137	1	2	2	2	16.726	7984.18029
138	1	2	2	2	13.565	8139.99243
139	1	2	2	2	16.529	8077.974
140	1	2	2	2	10.543	8158.30507
141	1	3	2	2	14.447	8059.82733
142	1	3	2	2	10.251	8163.20921
143	1	3	2	2	20.731	8180.19593
144	1	3	2	2	16.75	8109.40671
145	1	3	2	2	17.088	7976.55938
146	1	3	2	2	18.565	8007.11278
147	1	3	2	2	8.206	8472.92422
148	1	3	2	2	8.191	7863.54272
149	1	3	2	2	10.86	8181.45963
150	1	3	2	2	21.109	8012.74219
151	1	1	3	2	11.751	8535.6761
152	1	1	3	2	11.73	8075.41975
153	1	1	3	2	10.583	8252.95034
154	1	1	3	2	16.624	8243.95071
155	1	1	3	2	22.545	8246.46452
156	1	1	3	2	11.243	8205.4418
157	1	1	3	2	9.125	8409.5744
158	1	1	3	2	11.743	8156.48952
159	1	1	3	2	12.751	7807.31127
160	1	1	3	2	8.601	8288.49797
161	1	2	3	2	13.3	8313.70953
162	1	2	3	2	14.747	7957.50537
163	1	2	3	2	11.999	8140.66772
164	1	2	3	2	13.437	8133.74539
165	1	2	3	2	15.014	7994.89005
166	1	2	3	2	9.753	8216.42229
167	1	2	3	2	8.013	8751.47172
168	1	2	3	2	11.103	7898.50514
169	1	2	3	2	11.633	7881.25005
170	1	2	3	2	13.767	7939.2073
171	1	3	3	2	16.777	8052.92763
172	1	3	3	2	16.509	8190.7131
173	1	3	3	2	9.422	7825.06354

174	1	3	3	2	13.782	8078.97807
175	1	3	3	2	25.073	7935.84446
176	1	3	3	2	11.684	8160.92985
177	1	3	3	2	10.661	8186.1493
178	1	3	3	2	11.469	8127.18555
179	1	3	3	2	19.221	7946.8413
180	1	3	3	2	14.852	8127.19437
181	1	1	1	3	33.256	8292.72798
182	1	1	1	3	37.898	8217.19487
183	1	1	1	3	32.379	7737.27671
184	1	1	1	3	42.625	8048.21429
185	1	1	1	3	36.348	8085.4311
186	1	1	1	3	42.668	8120.85684
187	1	1	1	3	14.883	8792.85101
188	1	1	1	3	43.681	8292.44911
189	1	1	1	3	41.507	8266.11941
190	1	1	1	3	27.765	8270.65103
191	1	2	1	3	27.122	8494.83581
192	1	2	1	3	26.332	8632.70865
193	1	2	1	3	27.074	8541.04623
194	1	2	1	3	36.833	8005.95212
195	1	2	1	3	25.503	8508.72527
196	1	2	1	3	27.802	8351.62888
197	1	2	1	3	28.718	7971.91525
198	1	2	1	3	31.96	8477.36287
199	1	2	1	3	26.936	8579.59213
200	1	2	1	3	30.521	8249.95433
201	1	3	1	3	32.89	8437.89742
202	1	3	1	3	20.369	8665.24551
203	1	3	1	3	31.786	8609.05808
204	1	3	1	3	33.49	8028.00794
205	1	3	1	3	26.733	8102.6436
206	1	3	1	3	51.578	7775.13342
207	1	3	1	3	30.417	8170.08549
208	1	3	1	3	25.086	8456.88246
209	1	3	1	3	36.234	8131.13788
210	1	3	1	3	37.845	8293.1064
211	1	1	2	3	21.562	8933.3027
212	1	1	2	3	13.192	7940.94234
213	1	1	2	3	25.738	8237.11338
214	1	1	2	3	14.845	8174.0505
215	1	1	2	3	42.124	7527.4962
216	1	1	2	3	11.618	8077.45006
217	1	1	2	3	31.703	7852.12878
218	1	1	2	3	9.905	8284.02408
219	1	1	2	3	33.781	8267.71416
220	1	1	2	3	13.808	8194.12599

221	1	2	2	3	38.162	8512.26659
222	1	2	2	3	40.673	8020.64114
223	1	2	2	3	23.425	7983.44312
224	1	2	2	3	26.959	8838.58142
225	1	2	2	3	32.679	8547.71939
226	1	2	2	3	33.341	8135.74867
227	1	2	2	3	21.526	8987.80934
228	1	2	2	3	26.763	8304.41723
229	1	2	2	3	40.53	7681.2127
230	1	2	2	3	31.681	8537.33921
231	1	3	2	3	38.936	7964.90907
232	1	3	2	3	31.026	7997.82592
233	1	3	2	3	31.559	8714.43436
234	1	3	2	3	41.405	8305.19661
235	1	3	2	3	36.895	8468.31972
236	1	3	2	3	23.173	8274.31516
237	1	3	2	3	24.669	8694.81616
238	1	3	2	3	31.015	8120.34208
239	1	3	2	3	35.454	7695.17004
240	1	3	2	3	31.665	8204.35965
241	1	1	3	3	25.305	8421.62808
242	1	1	3	3	32.781	8127.0811
243	1	1	3	3	29.068	8733.28908
244	1	1	3	3	23.529	8436.01275
245	1	1	3	3	21.57	8737.56543
246	1	1	3	3	29.674	8561.27055
247	1	1	3	3	23.785	8681.31789
248	1	1	3	3	30.495	8379.5523
249	1	1	3	3	23.768	8502.74256
250	1	1	3	3	22.273	8299.85339
251	1	2	3	3	31.945	8066.20094
252	1	2	3	3	28.505	8186.21516
253	1	2	3	3	35.197	8040.65473
254	1	2	3	3	28.728	8363.78388
255	1	2	3	3	22.639	8601.05363
256	1	2	3	3	38.688	8102.90552
257	1	2	3	3	19.201	8449.69923
258	1	2	3	3	30.811	7873.75198
259	1	2	3	3	30.445	8604.28793
260	1	2	3	3	17.352	8469.58559
261	1	3	3	3	27.127	8709.22026
262	1	3	3	3	31.177	8163.12054
263	1	3	3	3	32.384	8404.71461
264	1	3	3	3	48.012	8099.0295
265	1	3	3	3	21.378	9051.95121
266	1	3	3	3	27.605	8442.49942
267	1	3	3	3	18.074	8836.59712

268	1	3	3	3	24.015	8563.2085
269	1	3	3	3	23.544	8704.82452
270	1	3	3	3	23.367	8232.83103

MRP Model Output

Table 37 below shows the output data for all replications of the MRP model, boxed by treatment (10 replications per treatment).

Table 37: Output Data for All Replications - MRP Model

REP	SYS	D.U.	D.V.	LT VAR.	AWP DAYS	ANNUAL COST
1	1	1	1	1	0.009	12361.09907
2	1	1	1	1	0	12519.96647
3	1	1	1	1	0	12141.09578
4	1	1	1	1	0.008	12576.0551
5	1	1	1	1	0	12268.02875
6	1	1	1	1	0	12657.1823
7	1	1	1	1	0	12354.92761
8	1	1	1	1	0	9920.58789
9	1	1	1	1	0	12601.8375
10	1	1	1	1	0	12609.14143
11	1	2	1	1	0	11999.2213
12	1	2	1	1	0	12183.59375
13	1	2	1	1	0	12693.72342
14	1	2	1	1	0	11880.96129
15	1	2	1	1	0.003	12660.07661
16	1	2	1	1	0	12352.46078
17	1	2	1	1	0.005	12302.86926
18	1	2	1	1	0	12189.55894
19	1	2	1	1	0.051	12247.15154
20	1	2	1	1	0.102	12231.47822
21	1	3	1	1	0	12078.01679
22	1	3	1	1	0.014	12263.79354
23	1	3	1	1	0.028	12384.99436
24	1	3	1	1	0.004	12174.46563
25	1	3	1	1	0.018	12240.67721
26	1	3	1	1	0.027	12606.31309

27	1	3	1	1	0.032	12090.08783
28	1	3	1	1	0	12518.82613
29	1	3	1	1	0	12097.44509
30	1	3	1	1	0	12498.29883
31	1	1	2	1	0.025	12497.90795
32	1	1	2	1	0	12256.97428
33	1	1	2	1	0	12024.16434
34	1	1	2	1	0	12235.55642
35	1	1	2	1	0.001	12278.41101
36	1	1	2	1	0.017	12086.66836
37	1	1	2	1	0	12507.97698
38	1	1	2	1	0.004	12814.30413
39	1	1	2	1	0.013	12518.81098
40	1	1	2	1	0	12532.40297
41	1	2	2	1	0	12206.5354
42	1	2	2	1	0.003	12692.08297
43	1	2	2	1	0.004	12358.19818
44	1	2	2	1	0	12403.23937
45	1	2	2	1	0	12075.23119
46	1	2	2	1	0.018	12368.72418
47	1	2	2	1	0.066	12485.14683
48	1	2	2	1	0	12442.90394
49	1	2	2	1	0.066	12408.75119
50	1	2	2	1	0.026	12479.83088
51	1	3	2	1	0.07	12458.25247
52	1	3	2	1	0.054	11763.85977
53	1	3	2	1	0.015	12367.50496
54	1	3	2	1	0	12738.37511
55	1	3	2	1	0.027	12055.92213
56	1	3	2	1	0	12364.26672
57	1	3	2	1	0	12692.41301
58	1	3	2	1	0	12394.68242
59	1	3	2	1	0	12804.46237
60	1	3	2	1	0	12460.20052
61	1	1	3	1	0.02	12019.05491
62	1	1	3	1	0.134	12321.46679
63	1	1	3	1	0	12428.19588
64	1	1	3	1	0	12611.88226
65	1	1	3	1	0.136	11592.21717
66	1	1	3	1	0	11888.83552
67	1	1	3	1	0.02	12345.79921
68	1	1	3	1	0	12287.4114
69	1	1	3	1	0	12604.47345
70	1	1	3	1	0	12467.53439
71	1	2	3	1	0	12393.58672
72	1	2	3	1	0.039	12107.67786
73	1	2	3	1	0.033	12394.61068

74	1	2	3	1	0.128	12802.24939
75	1	2	3	1	0.103	12343.89881
76	1	2	3	1	0.004	12412.32648
77	1	2	3	1	0	11867.17322
78	1	2	3	1	0	11774.69354
79	1	2	3	1	0.005	11983.43078
80	1	2	3	1	0.03	12263.7908
81	1	3	3	1	0.005	12286.44337
82	1	3	3	1	0.021	12232.22731
83	1	3	3	1	0.135	12085.38041
84	1	3	3	1	0.018	12714.34229
85	1	3	3	1	0	12904.96013
86	1	3	3	1	0.003	12268.19021
87	1	3	3	1	0	12294.09824
88	1	3	3	1	0.001	12285.19268
89	1	3	3	1	0.089	12405.60992
90	1	3	3	1	0.001	11968.60394
91	1	1	1	2	0.615	11993.649
92	1	1	1	2	0.384	11380.09102
93	1	1	1	2	0.808	11681.79376
94	1	1	1	2	0.214	11722.46215
95	1	1	1	2	0.203	11941.9321
96	1	1	1	2	0	12109.45972
97	1	1	1	2	0.098	12003.67542
98	1	1	1	2	0.186	11396.09744
99	1	1	1	2	0.217	11900.31069
100	1	1	1	2	0.374	11840.68994
101	1	2	1	2	0.69	11642.80327
102	1	2	1	2	0.244	11601.37115
103	1	2	1	2	1.072	11625.69667
104	1	2	1	2	0.037	11641.39301
105	1	2	1	2	1.41	11340.15918
106	1	2	1	2	0.398	11752.91434
107	1	2	1	2	0.15	11638.08617
108	1	2	1	2	0.541	11885.50864
109	1	2	1	2	0.477	11707.54679
110	1	2	1	2	0.087	11938.85013
111	1	3	1	2	0.615	11425.01478
112	1	3	1	2	0.087	11410.00382
113	1	3	1	2	1.576	11789.29737
114	1	3	1	2	0.334	11921.55994
115	1	3	1	2	0.048	12022.80261
116	1	3	1	2	0.297	11762.68486
117	1	3	1	2	1.452	11143.67816
118	1	3	1	2	1.6	11930.15543
119	1	3	1	2	0.352	11852.75043
120	1	3	1	2	0.689	11881.73644

121	1	1	2	2	0.224	11978.10791
122	1	1	2	2	0.918	11524.85933
123	1	1	2	2	0.279	11809.03249
124	1	1	2	2	1.364	11647.14475
125	1	1	2	2	0.359	11927.10373
126	1	1	2	2	2.289	11451.92075
127	1	1	2	2	0.076	11745.22559
128	1	1	2	2	0.979	11631.09507
129	1	1	2	2	0.386	11973.72665
130	1	1	2	2	0.385	11675.95819
131	1	2	2	2	0.171	12108.81661
132	1	2	2	2	0.341	12004.24808
133	1	2	2	2	0.845	11996.7191
134	1	2	2	2	0.382	11763.65172
135	1	2	2	2	0.459	12191.74978
136	1	2	2	2	0.083	12018.55904
137	1	2	2	2	0.026	11822.49848
138	1	2	2	2	0.342	11533.11787
139	1	2	2	2	0.205	11527.72079
140	1	2	2	2	0	12037.06886
141	1	3	2	2	0.086	11615.65751
142	1	3	2	2	1.032	11555.31941
143	1	3	2	2	0.77	12013.44374
144	1	3	2	2	0.032	12356.91602
145	1	3	2	2	0.753	11923.7516
146	1	3	2	2	0.025	12025.61846
147	1	3	2	2	0.662	11343.67515
148	1	3	2	2	0.336	11695.88882
149	1	3	2	2	0.572	12087.09703
150	1	3	2	2	0.021	12596.17016
151	1	1	3	2	0.019	11998.17165
152	1	1	3	2	1.455	12022.54465
153	1	1	3	2	0.157	11695.93635
154	1	1	3	2	0.397	12301.92972
155	1	1	3	2	0.617	11442.854
156	1	1	3	2	0	12182.68217
157	1	1	3	2	0.126	11872.96213
158	1	1	3	2	0.25	11555.04203
159	1	1	3	2	0.112	11744.84608
160	1	1	3	2	0.334	11976.20607
161	1	2	3	2	0.032	12084.8071
162	1	2	3	2	0.778	11991.62691
163	1	2	3	2	0.302	12091.00617
164	1	2	3	2	2.652	11490.25481
165	1	2	3	2	0.652	11627.62333
166	1	2	3	2	0.369	12133.77582
167	1	2	3	2	0.315	12066.06346

168	1	2	3	2	0.005	11843.69158
169	1	2	3	2	0.468	11663.13185
170	1	2	3	2	0.015	11995.70718
171	1	3	3	2	0.408	11924.07688
172	1	3	3	2	1.222	11813.7788
173	1	3	3	2	0.623	11878.67148
174	1	3	3	2	1.455	11379.02218
175	1	3	3	2	0.282	12222.36908
176	1	3	3	2	0.131	12009.04915
177	1	3	3	2	0.364	11834.66793
178	1	3	3	2	1.19	11707.66922
179	1	3	3	2	0.202	12246.40939
180	1	3	3	2	1.463	11478.96103
181	1	1	1	3	2.338	11842.75773
182	1	1	1	3	0.89	11817.65961
183	1	1	1	3	6.966	11865.39591
184	1	1	1	3	2.739	11842.82589
185	1	1	1	3	2.935	11772.22622
186	1	1	1	3	7.202	11562.84075
187	1	1	1	3	4.427	12180.75942
188	1	1	1	3	2.236	11925.85946
189	1	1	1	3	1.448	11626.33225
190	1	1	1	3	0.67	12124.40673
191	1	2	1	3	2.671	11578.50518
192	1	2	1	3	3.832	11713.16422
193	1	2	1	3	2.034	11609.63454
194	1	2	1	3	7.737	11427.7026
195	1	2	1	3	7.044	11621.52356
196	1	2	1	3	5.218	11911.88584
197	1	2	1	3	7.019	11668.25234
198	1	2	1	3	6.885	11304.8293
199	1	2	1	3	4.492	11987.84903
200	1	2	1	3	2.816	11758.12424
201	1	3	1	3	1.86	11275.21901
202	1	3	1	3	1.229	12208.83665
203	1	3	1	3	1.461	11777.10606
204	1	3	1	3	3.355	12152.83944
205	1	3	1	3	2.546	11421.40587
206	1	3	1	3	2.828	11172.32748
207	1	3	1	3	0.851	11829.46624
208	1	3	1	3	0.337	11946.96886
209	1	3	1	3	5.994	11086.63516
210	1	3	1	3	1.176	12047.85966
211	1	1	2	3	5.081	11811.46442
212	1	1	2	3	5.256	11589.46566
213	1	1	2	3	4.823	11231.76687
214	1	1	2	3	0.305	12284.52361

215	1	1	2	3	2.545	11720.48763
216	1	1	2	3	2.155	11850.303
217	1	1	2	3	3.317	11361.32015
218	1	1	2	3	3.024	11754.30468
219	1	1	2	3	3.891	12301.42637
220	1	1	2	3	2.386	11801.90993
221	1	2	2	3	8.177	11651.63595
222	1	2	2	3	3.235	11984.81553
223	1	2	2	3	8.246	11866.75575
224	1	2	2	3	0.783	11795.41955
225	1	2	2	3	3.139	12009.23463
226	1	2	2	3	5.285	11715.37272
227	1	2	2	3	2.173	11540.32321
228	1	2	2	3	2.105	11189.5028
229	1	2	2	3	5.191	11465.24722
230	1	2	2	3	5.619	11430.14232
231	1	3	2	3	3.276	12022.27977
232	1	3	2	3	1.495	12199.36065
233	1	3	2	3	0.563	11933.6038
234	1	3	2	3	3.344	12483.04468
235	1	3	2	3	4.849	11738.4837
236	1	3	2	3	5.988	11593.79827
237	1	3	2	3	2.64	11952.34446
238	1	3	2	3	3.085	11738.30555
239	1	3	2	3	0.561	11938.26399
240	1	3	2	3	1.659	11777.36821
241	1	1	3	3	2.548	11868.00212
242	1	1	3	3	9.326	12334.08063
243	1	1	3	3	7.853	12042.13025
244	1	1	3	3	2.28	12269.11493
245	1	1	3	3	1.07	11540.32857
246	1	1	3	3	1.72	12280.37721
247	1	1	3	3	5.938	10990.37293
248	1	1	3	3	1.436	11511.05219
249	1	1	3	3	2.225	11777.63828
250	1	1	3	3	2.368	12142.36653
251	1	2	3	3	1.446	12237.33157
252	1	2	3	3	0.325	12262.45056
253	1	2	3	3	5.385	11401.63789
254	1	2	3	3	2.954	11891.64749
255	1	2	3	3	3.964	11307.83164
256	1	2	3	3	1.834	11751.61919
257	1	2	3	3	1.273	11770.92104
258	1	2	3	3	4.103	11496.1455
259	1	2	3	3	2.62	12348.8104
260	1	2	3	3	0.963	12484.65992
261	1	3	3	3	10.602	11802.57361

262	1	3	3	3	9.23	11979.22763
263	1	3	3	3	5.8	11885.08835
264	1	3	3	3	3.312	11639.57686
265	1	3	3	3	2.506	12055.77751
266	1	3	3	3	3.434	12028.06708
267	1	3	3	3	7.285	11717.24587
268	1	3	3	3	8.405	12036.72041
269	1	3	3	3	6.033	12037.93252
270	1	3	3	3	3.579	11875.33757

Appendix E: Simulation Model Array Layout

	P/N	CQ	OCM	LT S.D.	% REP	RF	RT	O/H	B/O	EOQ	ROP	LT	CUM LT	UNIT COST	HC	OC
GR	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	...
SR	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	...
O/H	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	...
NR	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	...
PO Rec	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	...
PO Rel	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	...

Figure 48: Sample Item Array (First 16 Columns Only)

ARRAY LEGEND

P/N	Item Part Number
CQ	Current Quarter Production/Usage
OCM	% On-Condition Maintenance Repair
LT S.D.	Standard Deviation of the Lead Time (expressed as Cv)
% REP	Not Used
RF	Replacement Factor
RT	Repair Time (in days)
O/H	On-hand Balance
B/O	Number of Units on Backorder
EOQ	Current Economic Order Quantity
ROP	Current Reorder Point
LT	Mean Lead Time (in days)
CUM LT	Cumulative Lead Time of Item Plus Higher Level Assemblies
UNIT COST	Unit Cost of Item
HC	Holding Cost (in dollars per unit per year)
OC	Ordering Cost (in dollars per order)

The remaining array data elements are used for MRP regeneration only. The numbers in Figure 48 refer to the week (i.e.. "0" refers to the current week, "1" to the next week, and so on)

GR	Gross Requirements for Schedule Week
SR	Scheduled Receipts for Schedule Week
O/H	On-Hand Balance for Schedule Week
NR	Net Requirements for Schedule Week
PORec	Planned Order Receipts for Schedule Week
PORel	Planned Order Release for Schedule Week

Bibliography

Abell, John B. and Frederick W. Finnegan. Data and Data Processing Issues in the Estimation of Requirements for Aircraft Recoverable Spares and Depot Repair. Contract F49620-91-C-0003. Santa Monica CA: The RAND Corporation, 1993 (AD-A282351).

Air Force Materiel Command. *Consumable Item Requirements Determination.* AFMC Instruction 23-105. Wright-Patterson AFB OH: HQ AFMC, 28 April 1997.

Anderson, John C., Roger G. Schroeder, Sharon E. Tupy, and Edna M. White. "Material Requirements Planning Systems: The State of the Art," *Production and Inventory Management, 23*: 51-67 (Fourth Quarter 1982).

APICS *Dictionary*. Falls Church VA: American Production and Inventory Control Society, 1984.

Axsater, Sven and Kaj Rosling. "Multi-level Production-Inventory Control: Material Requirements Planning or Reorder Point Policies," *European Journal of Operational Research, 75*: 405-412 (June 9, 1994).

Banks, Jerry, John S. Carlson II, and Barry L. Nelson. *Discrete-Event System Simulation, 2d ed.* New Jersey: Prentice Hall, 1996.

Barrett, Robert T. and R. Lawrence LaForge. "A Study of Replanning Frequencies in a Material Requirements Planning System," *Computers and Operations Research, 18*: 569-578 (1991).

Berry, Harry A. and Edward E. Tatge. An Evaluation of the Appropriateness of the Defense Logistics Agency's Requirements Model. MS Thesis. AFIT/GIM/LAL/95S-1. Graduate School of Logistics and Acquisition Management, Air Force Institute of Technology (AU), Wright-Patterson AFB OH, September 1995 (AD-A300454).

Blackburn, Joseph D., Dean H. Kropp, and Robert A. McMillen. "A Comparison of Strategies to Dampen Nervousness in MRP Systems," *Management Science, 32*: 413-429 (April 1986).

Blazer, D. J., W. Faulkner, and M. P. Ham. EOQ (Economic Order Quantity) Range Model. Maxwell AFB Gunter Annex AL: Air Force Logistics Management Center, January 1985 (AD-A153709).

Bobko, Peter B. and D. Clay Whybark. "The Coefficient of Variation as a Factor in MRP Research," *Decision Sciences, 16*: 421-434 (Fall 1985).

Brennan, L. and S. M. Gupta. "A Structured Analysis of Material Requirements Planning Systems Under Combined Demand and Supply Uncertainty," *International Journal of Production Research, 31*: 1689-1707 (July 1993).

Buzacott, J. A. and J. G. Shanthi Kumar. "Safety Stock Versus Safety Time in MRP Controlled Production Systems," *Management Science, 40*: 1678-1689 (December 1994).

CACI. *Repairability Forecast Model Background Paper.* August 1996.

-----. *Repairability Forecast Model Users Manual.* July 1997.

Chalmet, Luc G., Marc DeBodt, and Luk Van Wassenhove. "The Effect of Engineering Changes and Demand Uncertainty on MRP Lot Sizing: A Case Study," *International Journal of Production Research, 23*: 233-251 (1985).

Chang, C. Alec. "The Interchangeability of Safety Stocks and Safety Lead Time," *Journal of Operations Management, 6*: 35-42 (November 1985).

Chase, Richard B. and Nicholas J. Aquilano. *Production and Operations Management, 6th ed.* Burr Ridge IL: Irwin, 1992.

DeBodt, Marc A. and Luk N. Van Wassenhove. "Cost Increases Due to Demand Uncertainty in MRP Lot Sizing," *Decision Sciences, 14*: 345-362 (July 1983).

Demmy, W. Steven and Anthony J. Giambrone. "MRP II in AFLC Maintenance Planning and Control." *Air Force Journal of Logistics, 14*, no. 4: 7-11 (Fall 1990).

Department of the Air Force. *Determining Materiel Requirement for Air Force-Managed Consumable Items*. AFI 23-103. Washington: HQ USAF, 6 June 1994.

Draper, Ernie. "Repairability Forecast Model." Briefing to OC-ALC/LPP. Oklahoma City Air Logistics Center, Tinker AFB OK, 21 May 1997.

Dussault, Christian J. H. Evaluation of Air Force and Navy Demand Forecasting Systems. MS Thesis. AFIT/GLM/LAL/95M-1. Graduate School of Logistics and Acquisition Management, Air Force Institute of Technology (AU), Wright-Patterson AFB OH, March 1995 (AD-A285299).

Dynamics Research Corporation. LPP Lean Logistics Material Support: Benchmark Findings and Analysis: Final Report. Contract Number F34601-95-D-0374/0020. Andover MA: Dynamics Research Corporation, 28 February 1997.

Estep, John A. "Tailoring Your MRP System to Meet Your Needs," *Industrial Engineering Solutions, 28*: 36-39 (September 1996).

Etienne, Eisenhower C. "Choosing Optimal Buffering Strategies for Dealing With Uncertainty in MRP," *Journal of Operations Management, 7*: 107-120 (October 1987).

Faulkner, James M. The Impact of MRP II Implementation at Ogden Air Logistics Center on Future Air Force Logistics Command Implementations. Master's Thesis. AFIT/GSM/LSG/89S-21. School of Systems and Logistics, Air Force Institute of Technology (AU), Wright-Patterson AFB OH, September 1989 (AD-A215746).

Finnern, Michael L. A Case Study of the Implementation of Manufacturing Resource Planning at the Ogden Air Logistics Center. Master's Thesis. AFIT/GLM/LSM/88S-18. School of Systems and Logistics, Air Force Institute of Technology (AU), Wright-Patterson AFB OH, September 1988 (AD-A201565).

Gaetano, Mark and Douglas J. Blazer. Wholesale EOQ (Economic Order Quantity) Safety Level. Wright-Patterson AFB OH: Air Force Logistics Command, April 1988 (AD-A199167).

General Accounting Office. Air Force Logistics System Modernization Projects. Report Number IMTEC-89-42. Washington: Government Printing Office, April 1989.

-----. Best Management Practices: Reengineering the Air Force's Logistics System Can Yield Substantial Savings. Report Number NSIAD-96-5. Washington: Government Printing Office, February 1996a.

-----. Defense Business Operation Fund: Management Issues Challenge Fund Implementation. Report Number AIMD-95-79. Washington: Government Printing Office, March 1995a.

-----. Defense Inventory Management: Problems, Progress, and Additional Actions Needed. Report Number T-NSIAD-97-109. Washington: Government Printing Office, March 1997a.

-----. Defense Logistics: Requirement Determinations for Aviation Spare Parts Need to Be Improved. Report Number NSIAD-96-70. Washington: Government Printing Office, March 1996b.

-----. Defense Supply: Acquisition Leadtime Requirements Can Be Significantly Reduced. Report Number NSIAD-95-2. Washington: Government Printing Office, December 1994.

-----. Depot Maintenance: Opportunities to Privatize Repair of Military Engines. Report Number NSIAD-96-33. Washington: Government Printing Office, March 1996c.

-----. Depot Maintenance System Development Risks Are High. Report Number IMTEC-90-46. Washington: Government Printing Office, May 1990.

-----. High-Risk Series: Defense Inventory Management. Report Number HR-95-5. Washington: Government Printing Office, February 1995b.

-----. High-Risk Series: Defense Inventory Management. Report Number HR-97-5. Washington: Government Printing Office, February 1997b.

-----. Inventory Management: DoD Can Build on Progress in Using Best Practices to Achieve Substantial Savings. Report Number NSIAD-95-142. Washington: Government Printing Office, August 1995c.

-----. Inventory Management: Greater Use of Best Practices Could Reduce DoD's Logistics Costs. Report Number T-NSIAD-97-214. Washington: Government Printing Office, July 1997c.

Goulet, Wayne C. and Michael L. Rollman. A Study of Defense Logistics Agency Inventory Classifications: Application of Inventory Control Methods to Reduce Total Variable Cost and Stockage Levels. MS Thesis. AFIT/GTM/LAL/96S-6. Graduate School of Logistics and Acquisition Management, Air Force Institute of Technology (AU), Wright-Patterson AFB OH, September 1996 (AD-A319931).

Grasso, Edward T. and Bernard W. Taylor III. "A Simulation-Based Experimental Investigation of Supply/Timing Uncertainty in MRP Systems," *International Journal of Production Research, 22*: 485-497 (May/June 1984).

Gupta, Sanjeev. "Supply Chain Management in Complex Manufacturing," *Industrial Engineering Solutions, 29*: 18-21 (March 1997).

Gupta, Surendra M. and Louis Brennan. "A Knowledge Based System for Combined Just-In-Time and Material Requirements Planning," *Computers and Electrical Engineering, 19*: 157-174 (March 1993).

Hanks, Christopher H. How DLA's Supply Performance Affects Air Force Readiness. Contract Number MDA903-85-C-0139. Bethesda MD: Logistics Management Institute, October 1990 (AD-A230291).

Hanks, Christopher H. Weapon-System-Oriented Supply Management at DLA: Relating Inventory Investment to Readiness. Contract Number MDA903-90-C-0006. Bethesda MD: Logistics Management Institute, March 1993 (AD-A268674).

Hanks, Christopher H. and Tovey C. Bachman. Improving System Safety Levels at the Defense Logistics Agency. Contract Number MDA903-90-C-0006. Bethesda MD: Logistics Management Institute, August 1993.

Hodges, James S. "Six (Or So) Things You Can Do With a Bad Model," *Operations Research, 39*: 355-365 (May-June 1991).

Jacobs, F. Robert and D. Clay Whybark. "A Comparison of Reorder Point and Material Requirements Planning Inventory Control Logic," *Decision Science, 23*: 332-342 (March/April 1992).

Kanet, John J. "MRP 96: Time to Rethink Manufacturing Logistics." *Production and Inventory Management Journal, 29*, no.2: 57-61 (Second Quarter 1988).

Kropp, Dean H. and Robert C. Carlson. "A Lot-Sizing Algorithm for Reducing Nervousness in MRP Systems," *Management Science, 30*: 240-244 (February 1984).

Kropp, Dean H., Robert C. Carlson, and James V. Jucker. "Heuristic Lot-Sizing Approaches for Dealing with MRP System Nervousness," *Decision Sciences, 14*: 156-169 (April 1983).

Law, Averill M. and W. David Kelton. *Simulation Modeling and Analysis, 2d ed.* New York: McGraw-Hill, 1991.

Lee, T. S. and Everett E. Adam, Jr. "Forecasting Error Evaluation in Material Requirements Planning (MRP) Production-Inventory Systems," *Management Science, 32*: 1186-1205 (September 1986).

Long, William S. and Douglas H. Engberson. The Effects of Violations of the Constant Demand Assumption on the Defense Logistics Agency Requirements Model. MS Thesis. AFIT/GLM/LAL/94S-15. Graduate School of Logistics and Acquisition Management, Air Force Institute of Technology (AU), Wright-Patterson AFB OH, September 1994 (AD-A285272).

Matsuura, Haruki and Hitoshi Tsubone. "Determining Net Requirements for Material Requirements Planning," *OR: Journal of the Operational Research Society, 42*: 981-990 (November 1991).

McClave, James T. and P. George Benson. *Statistics for Business and Economics, 6th ed.* Englewood Cliffs NJ: Prentice-Hall Inc., 1994.

Meinich, Morten. An Assessment of Relevant Costs in the Wilson EOQ (Economic Order Quantity) Model. Master's Thesis. Naval Postgraduate School, Monterey CA, December 1988 (AD-A205666).

Montgomery, Douglas C. *Design and Analysis of Experiments, 3d ed.* New York: John Wiley & Sons, 1991.

Oklahoma City Air Logistics Center. *Lean Logistics Operating Instruction*. Draft OC-ALC/LLP OI FX-1. Tinker AFB OK: OC-ALC/LLP, 2 June 1998.

Pritzker, A. Alan B. *Introduction to Simulation and SLAM II, 4th ed.* New York: John Wiley & Sons, 1995.

Pritzker, A. Alan B., Jean J. O'Reilly, and David K. LaVal. *Simulation with Visual SLAM and AweSim*. New York: John Wiley & Sons, 1997.

Robillard, Glenn C. A Wholesale Level Consumable Item Inventory Model for Non-Stationary Demand Patterns. Monterey CA: Naval Postgraduate School, March 1994 (AD-A292401).

Schroeder, Roger G. *Operations Management: Decision Making in the Operations Function, 4th ed.* New York: McGraw-Hill, 1993.

Severs, Jefferson L. The DISASTER™ Scheduling System: A Review and Case Analysis. Master's Thesis. AFIT/GLM/LSM/91S-56. School of Systems and Logistics, Air Force Institute of Technology (AU), Wright-Patterson AFB OH, September 1991 (AD-A246758).

Statistix® for Windows User's Manual. Tallahassee FL: Analytical Software, 1996.

Tersine, Richard J. *Principles of Inventory and Materials Management, 4th ed.* New Jersey: Prentice-Hall, 1994.

Vollmann, Thomas E., William L. Berry, and D. Clay Whybark. *Manufacturing Planning and Control Systems, 3d ed.* Homewood IL: Irwin, 1992.

Wallace, Thomas F. *MRP II: Making It Happen.* Essex Junction VT: Oliver Wight Publications, 1990.

Whybark, D. Clay and J. Gregg Williams. "Material Requirements Planning Under Uncertainty," *Decision Sciences, 7*: 595-606 (October 1976).

Yano, Candace Arai and Robert C. Carlson. "Interaction Between Frequency of Rescheduling and the Role of Safety Stock in Material Requirements Planning Systems," *International Journal of Production Research, 25*: 221-232 (February 1987).

Zhao, X., J. C. Goodale, and T. S. Lee. "Lot-Sizing Rules and Freezing the Master Production Schedule in Material Requirements Planning Systems Under Demand Uncertainty," *International Journal of Production Research, 33*: 2241-2276 (August 1995).

Vita

Captain Kevin J. Gaudette was born on 1 October 1968 in Worcester, Massachusetts. He was raised in Spencer, Massachusetts and graduated from David Prouty High School in 1986. From there he went on to earn a Bachelor of Science degree in Mechanical Engineering in 1990 from the University of Vermont in Burlington, Vermont. He concurrently received his commission as a distinguished graduate from AFROTC.

Following graduation, Captain Gaudette was assigned to the 366th Supply Squadron at Mountain Home AFB. He was reassigned in December 1992 to the 39th Supply Squadron at Incirlik AB, Turkey. While there, he supported Operation PROVIDE COMFORT as Chief, Materiel Management Flight and as Chief, Operations Support Flight. Returning to CONUS in March 1994, he was assigned as the Chief of Resource Management for the 319th Recruiting Squadron in Portsmouth, New Hampshire. While there, he earned a Master of Business Administration degree from New Hampshire College in Manchester, New Hampshire. In February 1996, Captain Gaudette was again reassigned to the Joint Tactical Information Distribution System (JTIDS) Joint Program Office at Hanscom AFB, Massachusetts. While there, he served as the Executive Officer to the Program Director, and as the Chief, Acquisition Strategy Integrated Process Team.

In March 1997, Captain Gaudette attended Squadron Officer School in residence, and immediately proceeded to AFIT in May to pursue a Master of Science degree in Logistics Management. Upon graduation he will be assigned to the Air Force Logistics Management Agency at Maxwell AFB Gunter Annex, Alabama.

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13. ABSTRACT (*Maximum 200 Words*)

The Department of Defense has historically relied on Wilson's Economic Order Quantity (EOQ) model for consumable item management at all levels. With inventory practices under intense Congressional scrutiny over the past decade, the Air Force Materiel Command has searched for alternative systems to better manage its consumable inventory. Material Requirements Planning (MRP) is one such system, as is the MRP-based Repairability Forecast Model (RFM) developed by CACI. This thesis examines the wisdom of applying MRP logic in a remanufacturing environment. MRP has had some degree of success in environments where requirements are relatively certain and demand and lead time variability are not excessive. A remanufacturing operation, in contrast, is typified by a great deal of variability and uncertainty due to the very nature of repair.

The experimental methodology involved the development of computer simulation models of EOQ and MRP systems. Demand uncertainty, demand variability, and lead time variability were then varied at three levels each to develop a full factorial experimental design. The results were used to test EOQ and MRP using two different performance measures: average number of awaiting parts (AWP) days per repair and total annual inventory cost.

The results lend support for the use of MRP in a remanufacturing environment. The number of AWP days was significantly reduced from that of the EOQ system, albeit at an increased inventory cost. When the two measures are combined, however, MRP appears to outperform EOQ in aggregate.

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